Economics of Biological Invasion: Hound's Tongue (*Cynoglossum officinale*) and Livestock Production in British Columbia

by

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RESEARCH PROJECT SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF RESOURCE MANAGEMENT

in the
School of Resource and Environmental Management
Faculty of Environment

Report No. 529

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SIMON FRASER UNIVERSITY

Spring 2012

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Report Number:	**529**
Title of Research Project:	***Economics of Biological Invasion: Hound's Tongue (Cynoglossum officinale) and Livestock Production in British Columbia***

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Abstract

The exotic plant known as hound's tongue *(Cynoglossum officinale)* invades rangelands in British Columbia (BC) and creates economic welfare losses to ranchers and the broader society through declining rangeland productivity, recreation opportunities, and soil fertility. In addition to such adverse effects, hound's tongue also disperses "burrs" that infest cattle and reduce their market value. I assume that a representative rancher attempts to maximize the profits from livestock sales subject to the growth of hound's tongue in nearby rangelands. I develop a bio-economic model to demonstrate this management problem and derive the optimal allocation of labour for pulling hound's tongue and the area of infested land at the steady state. My research findings show that the private steady state equilibrium is not considerably different from the social steady state equilibrium. Furthermore, a private rancher may be willing to control hound's tongue in the neighbouring rangelands, once the marginal benefits from controlling hound's tongue in his or her own rangeland becomes less than the marginal benefits of controlling hound's tongue in the neighbouring public rangeland. Under such circumstances, government intervention to control hound's tongue may yield few incremental social benefits. The findings of this study may have implications for the design of invasive plant management strategies. Instead of direct government intervention, offering incentives to private ranchers may be appropriate for controlling invaders such as hound's tongue in rangelands in BC or elsewhere. If the intent of invasive plant management strategy is to provide support to ranchers more generally, then this may be better achieved via other means.

Key words: Bio-economic model; economic welfare loss; ranchers; forage loss; and producer surplus

Dedication

TO MY MOTHER

Acknowledgements

First and foremost, I would like to thank my senior supervisor, Dr. Duncan Knowler, for his guidance, dedication, and mentorship throughout the project. I would also like to thank Dr. Ken Lertzman for providing input and comments, especially on the ecological aspects of the research project. It was a pleasure working with both of them and I appreciate the time they dedicated to my project. The Invasive plant Council of British Columbia (IPCBC), Pacific institute for Climate solution (PICS) and Climate Change Impact Research Consortium (CCIRC) provided the funding and the opportunity to do this research. I would also like to thank several individuals and groups for their assistance to carry out this research. Dr. Judith Myers (University of British Columbia), Dr. Rose De Clerck-Floate (Research Centre, Lethbridge) Dr. Linda Wilson (Ministry of Agriculture and Land), AERE 2011 summer conference and PICS research symposium participants provided useful information for the purposes of my research. My special thanks go to Ann Skinner (Ministry of Forests and Range), and Lisa Scott (Eco Matters Consulting) for helping me to clarify various field level issues related to invasive plant species management in Okanagan, British Columbia. Finally, I would like to thank fellow REMMERS specifically David Kyobe, Patrick Kitchen, and Amy Suess for their editorial assistance at various stages of this research project.

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Acronyms

AERE	Association of Environmental & Resource Economists
CCIRC	Climate Change Impacts Research Consortium
IPCBC	Invasive Plant Council of British Columbia
MOAL	Ministry of Agriculture and Land
MOFR	Ministry of Forest and Range
NPV	Net Present Value
PICS	Pacific Institute for Climate Solutions

1. Introduction

Invasive alien weeds have become a serious economic threat to the agricultural sector in Canada and the United States (US). Pimentel et al. (2005) estimated that invasive plant species induced $27 billion in annual losses to the US economy. These losses consist of $24 billion in crop damages and $3 billion in herbicide treatment costs. Once invasive plant species become well established, they are typically difficult to control or to eradicate (Grimsrud, 2008). The best management strategies for controlling invasive plant species are usually associated with successful prevention and early detection (Perrings, et al., 2002). Protection against the establishment of new invasive plant species or controlling existing invasive plant species creates a substantial cost to private individuals and the wider society (Grimsrud, 2008). Some researchers have shown that invasive plant species are also associated with huge social costs such as habitat loss, biodiversity loss, and soil erosion etc (Duncan and Clark, 2005; Pimentel et al. 2005; Colautti et al., 2006).

The negative consequences of invasive plant species makes invasive plant management a complex issue for scientists and policy makers. In principle, private agents only take into account the private cost of invasion, and do not consider the social cost of invasion (Perrings, et al., 2010). This disregard of the social cost of invasion in production decisions may lead to a socially inefficient level of invasion and can generate welfare losses to the wider society. Due to such disregard of the social cost of invasion, private ranch operations may also fail to implement socially optimal invasive plant management policies. Therefore, the role of the government in the management of invasive plant species is often considered to be fundamental.

Economic theory shows that private agents may not be interested in controlling invasive plant species as extensively as may be socially desirable, because benefits from control may have public good characteristics and not accruing specifically to the private agents (Perrings, et al., 2002; Perrings, et al., 2010). These characteristics of the benefits from controlling invasive plant species lead to a free rider problem, which can result in inefficient resource allocation due to the divergence between private and social benefits from control. Therefore, some researchers claim that the private steady state equilibrium fails to generate a socially optimal resource allocation related to invasive plant management (Grimsrud, 2008; Clark, 2010).

In this research, I consider both the private and social costs of invasion by an exotic plant species in rangelands in order to determine if there is a divergence between privately and socially optimal levels of control and, if so, how extensive this divergence might be. Surprisingly, I find that the divergence is negligible. This research finding is important for invasive plant management policy not only for the species in question, but perhaps for wider applications as well. Furthermore, I show that a private rancher allocates labour for pulling hound's tongue in the neighbouring rangeland when the marginal cost of control in his or her own land is greater than the marginal cost of control in the neighbouring rangeland. This finding also has important policy implications for the role of private ranchers as stewards in invasive plant management in rangelands (Quaas, et al., 2007; Teague, et al., 2009).

An investment in current control programs will also generate future benefits to both private individuals and the wider society (Perrings et al., 2002). Therefore, there is a trade-off between the current control of invasive plant species and future profitability of such programs. Taking into account such trade-offs between the current control and its future benefits are important for decision makers to implement economically efficient and socially optimal invasive plant management policies (Cacho, et al., 2008). To implement these policies, it is necessary to consider both the private and social costs of invasion and its' impacts on the economic welfare of the wider society. Therefore, this study intends to generate the economic welfare loss estimates which include both the private and social costs of invasion.

When an invasion occurs, a country or region has to reallocate scarce resources for controlling and eradicating invasive plant species. The use of scarce resources for controlling or eradicating invasive plant species creates opportunity costs for society. This means that using public expenditure for invasive plant management may prevent the necessary expenditure on health, education, and transport sectors in an economy. Therefore, decision makers who implement invasive plant management policies have to determine if the benefits of such control are sufficient relative to the cost of the best forgone alternative (McIntosh et al., 2009). To make such a decision on implementing invasive plant management policies, it is necessary to understand the magnitude of the economic impacts of invasive plant species on society. However, it is difficult to find such comprehensive economic damage estimates for BC or Canada (RNT, 2002; Colautti et al., 2006; Frid, et al., 2008). The estimates of economic damage I develop here provide information to policy makers for identifying trade-offs between invasive plant management programs and alternative resource used.

In British Columbia (BC), invasive plants have a huge economic impact on the agricultural, recreational, health, and industrial sectors (Colautti et al., 2006). Invasive plants may have a direct impact on human welfare through an immediate influence on utility (i.e. loss of visual amenity or health impacts) (Perrings et al., 2010). They may also cause an indirect impact on human welfare via the disruption of natural ecosystem functioning, as occurs when the population dynamics of valuable indigenous species are hindered and biodiversity is reduced or when the productivity of domestic crops and grasses decline (Knowler and Barbier, 2000; Barbier, 2001; Knowler, 2005). There is also a control cost associated with invasive plant management, and this should be included to reflect the complete picture of the social cost of biological invasion (Knowler, 2005; Grimsrud, 2008). Some researchers indicate that invasive plant species impose an invisible tax on society because they create externalities to various economic sectors such as agriculture, forestry, and international trade. They show that invasive plant species create not only private costs to individuals, but also social costs to society as a whole (Perrings, et al., 2002; Duncan and Clark, 2005; Colautti, et al., 2006). However, economic valuation studies on invasive plant species in Canada primarily consider the private cost of invasion due to the difficulties in measuring the social cost of invasion (RNT, 2002; Colautti et al., 2006; Fried, et al., 2008). Therefore, such studies do not provide adequate information for policy makers to identify socially optimal invasive plant management policies.

Currently, there is substantial debate among invasive plant specialists, policy makers, and civil society about formulating the effective invasive plant management strategy for BC. The literature review indicates that there are two popular views about invasive plant management in the province of BC (Invasive Plant Council of British

Columbia (IPCBC, 2011)). The IPCBC has proposed a community based resource management strategy for invasive plant management in the province (IPCBC, 2011). Federal government Invasive Alien Species Strategy for Canada (2004) shows that invasive plant species problem does not respect to political boundaries. Therefore, there should be a proper coordination between different levels of governments for the successful management of invasive plant species in Canada (IPCBC, 2011). Hence, the federal government invasive plant management strategy follows top-down planning approach for invasive plant management. However, my key informant interviews reveal that the provincial government is willing to do direct interventions for controlling invasive plant species because of the social benefits associated with such control. My study aims to contribute to the debate on invasive plant management strategies by measuring the economic damages caused by hound's tongue *(Cynoglossum officinale)* in the rangelands of Okanagan and identifying policy implications for invasive plant management.

Economic theory suggests that a reduction in the market demand for a commodity or an increase in production costs leads to reduced consumer and producer surpluses and a social welfare loss (Freeman, 1993). However, none of the previous studies in Canada that have analyzed the economic impact of invasive plant species have used the consumer and producer surplus approach to measure these losses (RNT, 2002; Colautti et al., 2006; Frid, et al., 2008). As a result, there are very few, if any economic analyses that quantify the economic impact of invasive plants in the province of BC. Furthermore, an absence of comprehensive economic analyses creates obstacles for policy makers to formulate economically efficient and ecologically sustainable invasive plant management policies. In part, this intends to fill the knowledge gap related to the appropriate welfare analysis of invasive plant species impacts by developing an integrated bio-economic model to analyze the social welfare loss from hound's tongue in BC. Such an integrated ecological-economic approach can help to identify invasive plant management policies that can improve the sustainable invasive plant management practices in the rangelands of BC.

The objectives of this study are to investigate the economic impact of biological invasion on rangelands through comparing the economic welfare losses to ranchers and to society as a whole to identify policy implications for the management of invasive plant species. In order to pursue these research objectives, I answer the following research questions:

(i) What are the impacts of biological invasion by a representative invasive plant species on the economic welfare of ranchers and what is the privately optimal response to the biological invader?

(ii) Does the socially optimal response of ranchers to the invasive plant species differ from the privately optimal response from a broader social perspective that includes damages occurring away from the ranch?

(iii) How do the privately and socially optimal responses of ranchers differ when the representative rancher can allocate labour to control invasive plant species not only in his or her own rangeland, but also in the neighbouring rangeland?

(iv) What policy implications from this study can improve invasive plant management in rangelands?

In answering these research questions, this paper makes three contributions to the literature of environmental/ecological economics. First, this paper takes into account the divergence between the private and social costs, and analyzes how this divergence affects invasive plant management in the Okanagan region of BC. In doing so, the paper identifies policy strategies that lead to the sustainable management of invasive plant species in the rangelands of BC. In addition, the paper presents a brief comparison of such a management strategy with the current BC governments' invasive plant management strategy. Second, the paper develops an ecological-economic approach that combines economics, ecology, policy, and management in measuring the economic impacts of invasive plants species in rangelands. The development of an integrated approach may provide new insight for future researchers to conduct economic valuation studies on the other invasive plant species in BC. The application of such an integrated approach to analyze the interdependency between ecological and economic systems provides information for policy makers to design economically efficient and ecologically sustainable invasive plant management policies. Third, this study uses a comprehensive economic approach, which takes producer surplus as a measure of economic welfare. Therefore, the economic damage estimates derived from this study can be used to identify trade-offs between the current control costs and future benefits from controlling invasive plant species. The identification of such trade-offs may help decision makers to better allocate scarce resources in invasive plant management.

Section 2 provides a brief review of previous studies on the economic impacts of controlling invasive plant species; Section 3 presents a brief description of the representative invasive plant species hound’s tongue (*Cynoglossum officinale)*. In Section 4, I discuss the divergence between the private and social costs and its’ implications for invasive plant management. Section 5 elaborates upon the theoretical foundation of valuing the economic impact of biological invasion. The bio-economic model for this management problem is presented in Section 6, along with the assumptions used and details concerning ranch operations in BC. In Section 7, I present this management problem in an optimal control framework and derive the private and social steady state optimization conditions for the control and state variables in the bio-economic model. I also elaborate upon the optimal control policy based on the time path analysis in this section. In section 8, I provide the empirical analysis of this study. Furthermore, in this section, I present results, discussion, sensitivity analysis, and limitations of the study. I discuss the importance of my research findings in formulating policies for invasive plant management in Section 9. In section 10, I present the conclusions of the study. Finally, I offer some recommendations for scientists and policy makers in valuing economic damages from invasive plant species and identify the study areas for further research.

2. Review of Previous Studies on Invasive Plant Species

Several studies in the recent literature of environmental and ecological economics have analyzed the economic impacts of invasive plant species, Shogren (2000), Knowler and Barbier (2000), Eiswerth and van Kooten (2002), Settle and Shogren (2002) and Eiswerth and Johnson (2002). These studies have focused on controlling non-native invasive plant species without addressing the role of management of native commercial plant species for their economic use and profitability. However, an invasion creates a risk of vulnerability for native plant species and this situation provides disincentives for society to protect such plant species (Ranjan et al., 2008; Clark, 2010). As a result, society may tend to over harvest the native resource stock in the short run.

This tendency of resource extraction indicates that the low conservation effort and high level harvesting effort would be an optimal response to the risk of invasion (Ranjan et al., 2008; Clark, 2010). However, such resource extraction behaviour may lead to a decline in the resilience of the ecosystem. Therefore, policy makers should provide incentives for resource users to avoid the over extraction of resources in response to the risk of biological invasion and thereby protect the resilience of the ecosystem (Pindyck, 1984; Ranjan et al., 2008). However, there are few studies in the literature of environmental and ecological economics that examine the provision of incentives to private agents for protecting the ecological resilience of the system (Ranjan et al., 2008; Epanchin-Niel et al., 2009).

In some cases, post-invasion survival of species and their profitability are determined by the native resource stock. In such situations, the invasive plant management problem becomes a more complex issue (Barbier, 2001). For example, Knowler and Barbier (2000) analyzed the economic welfare loss from invasive plant species in the predator-prey framework. They showed that the economic welfare loss from invasive plant species is determined by the difference between the pre-and post-invasion profit or producer surplus. However, their study does not take into account the role of prevention effort in the pre-invasion period to alter such damages from biological invasion. In addition, Knowler and Barbier (2000) consider the private cost of invasion and do not analyze the difference between the private and social responses in the management of invasive plant species.

As mentioned in the introduction, benefits generated from controlling invasive plant species have the characteristics of public good. As a result, some researchers have shown that private land owners or ranchers are reluctant to control invasive plant species even in their own rangelands (Grimsrud et al., 2008). This behaviour by private ranchers can create negative impacts on the conservation of natural resources. To overcome such negative impacts, some researchers advocate direct or indirect interventions to control invasive plant species (Perrings, et al., 2002; Perrings, et al., 2010). In direct intervention, the government can finance invasive plant control programs directly. On the other hand, in indirect intervention, the government can provide incentives (i.e. payment for ecosystem services) to private land owners for controlling invasive plant species (Perrings, et al., 2010). However, the literature on invasive plant species has not given enough attention to analyzing the nature and elements of such invasive plant management policies. Therefore, it is important for policy makers and resource managers to find alternative policy strategies that provide incentives for private ranchers to manage both the native resource stock (i.e. grass species) and invasive plant species. In my research, I attempt to identify such policy strategies by investigating the impacts of divergence between the private and social costs related to the management of invasive plant species in rangelands. In the next section, I provide a brief introduction to the representative invasive plant species that is used as a case study to measure the economic damages from an invasion in rangelands.

3. Hound's Tongue (*Cynoglossum officinale*) in Rangelands of British Columbia

In this study, I consider hound's tongue (*Cynoglossum officinale*) as a representative invasive plant species in measuring economic welfare loss. Hound's tongue was introduced to North America from Eurasia via cereal seed and arrived in BC in 1922 (Ministry of Agriculture and Lands, 2008). This plant is biennial and native to Eurasia and Asia (Upadhyaya and Cranston, 1991). It is not well adapted to drier climate of less than 30cm annual precipitation. Hound's tongue invades in forests, rangelands, and road sides in BC. Some research shows that there are more than 2000 (5000 acres) hectares of land that are infested by hound's tongue in BC (Ministry of Agriculture and Lands, 2008). Hound's tongue produces more than 600 burred seeds per plant (Upadhyaya and Cranston, 1991; MOFR, 2008). It is poisonous to domestic animals and wildlife species in rangelands. Hound's tongue not only creates damages to the wildlife species in rangelands, but also reduces recreational benefits such as hunting and wildlife watching. Furthermore, hound's tongue seeds disturb to the soil and the disturbance leads to a soil loss. The soil loss makes adverse impacts on the soil moisture and ground water availability (MOFR, 2008).

On the economic side, hound's tongue creates substantial impacts on cattle producers in BC. The adverse impacts created by hound's tongue are second only to the knapweeds, which are the most harmful noxious weed to ranchers in BC (Upadhyaya and Cranston, 1991). Hound's tongue competes with native grass species and displaces more nutritious forage in the rangelands of BC (Upadhyaya and Cranston, 1991; De Clerck Floate, 1997). Therefore, the invasion of hound's tongue in rangelands reduces the amount of forage available for consumption by cattle. Due to a reduction in the quantity of forage in the rangelands, ranchers have to purchase supplementary feed from the market, which reduces their profitability. In addition, hound's tongue is associated with abundant burrs on cow's hide and reduces their market value or increases cleaning cost. Hound's tongue infested animals also reduce the reputation of ranchers as sellers in the beef market (Upadhyaya and Cranston, 1991). This brief description reveals that the invasion of hound's tongue in rangelands can create considerable economic damages to cattle producers in BC (Widanage and Knowler, 2011).

There are several studies that analyzed the ecological impacts of hound's tongue in Canada, including the impact of bio-control on invading hound's tongue in rangelands. However, there are only few studies, which consider the economic aspects of the problem (Upadhyaya and Cranston, 1991; De Clerck Floate, 1997). Upadhyaya and Cranston (1991) estimated that a rancher takes 5 days to clean nutlets from 100 hound's tongue infested cows before sending them to the market. These researchers also pointed out that the cleaning process leads to animal stress and weight loss. The weight loss and cleaning expenses create an additional cost to ranchers in BC and generate adverse impacts on the economic profits of ranching enterprises (Upadhyaya and Cranston, 1991). Therefore, it is important to investigate the economic impacts of hound's tongue on ranching enterprises for identifying policy strategies for the sustainable management of invasive plant species in the rangelands.

I selected hound's tongue as a representative invasive plant from among known invasive plant species on rangelands. These include such species as diffuse knapweed (*Centaurea diffusa Lam*), leafy spurage (*Euphorbia esula* L.*),* cheat grass (*Bromus tectorum,* L.), dalmatian toadflax (*Linaria dalmatica* (L.) P. Mill), and hawkweeds (*Hieracium caespitosum dumort* and *Hieracium aurantiacum* L.). These invasive plant species can be categorised based on their life history, habitat where they grow, undesirability (noxious weed), ecological characteristics, evolutionary strategy, and nature of economic damages. Based on these ecological and economic characteristics, hound's tongue can be used to represent invasive plant species in rangelands in BC. For example, almost all of these rangeland invasive plant species are legally defined as noxious weed and grow in the same habitat (i.e. rangeland) are toxic to livestock and wildlife habitat (Duncan and Clark, 2005). Dense infestation of these plant species creates somewhat similar adverse impacts on natural ecosystems and nature reserves by fragmenting sensitive plants and animal habitat (Upadhyaya and Cranston, 1991; Duncan and Clark, 2005). Wind, human disturbance, transport, and the expansion of the ranching industry play a crucial role in the distribution of these rangeland species including hound's tongue (Duncan and Clark, 2005). Many of these plant species are deep-tap rooted, winter annual, and biennial plants. Typically these plants begin flowering from late June to September and produce seed. Considering these economic and ecological characteristics of these invasive plant species, I argue that hound`s tongue is a good candidate to represent rangeland invasive plant species in BC.

The invasion of hound's tongue may not only create the private costs to ranchers, but also generates welfare losses to the wider society. As a result, there is a considerable divergence between the private and social costs of invasion. However, some previous studies only focused the private cost of invasion and therefore failed to present economically efficient and socially optimal policy implications for invasive plant management in BC (RNT, 2002; Colautti et al., 2006). To identify such policies for invasive plant management, it is necessary to consider both the private and social costs of invasion related to the representative ranching enterprise.

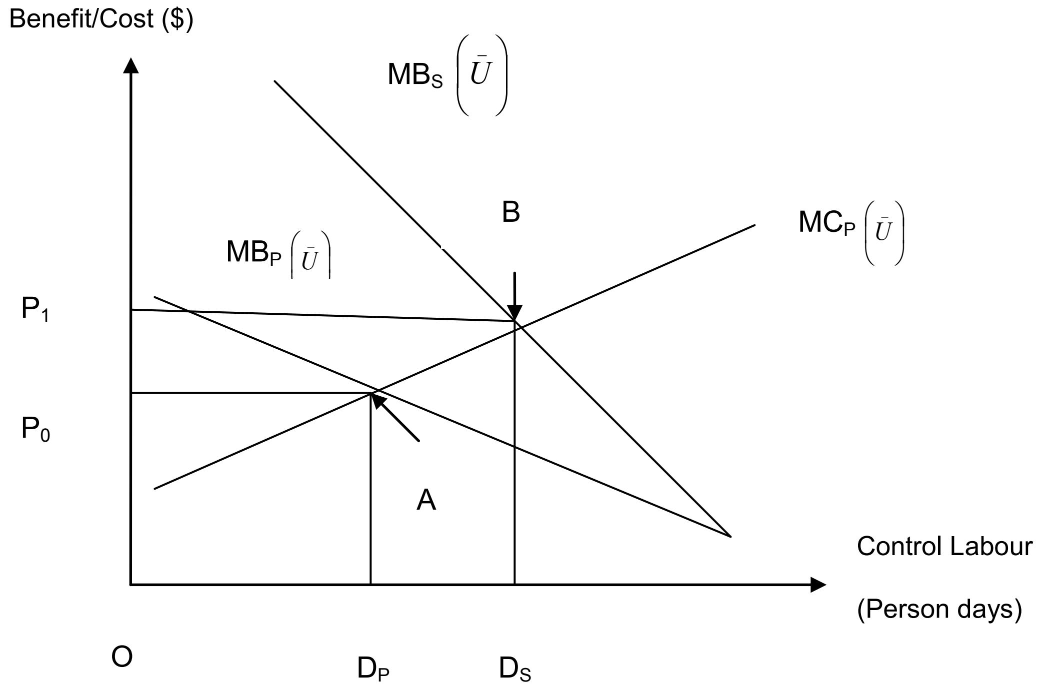
4. Private and Social Cost of Invasion

The invasion of hound's tongue in the rangelands of BC creates both private and social costs to ranchers and society respectively. The private cost of hound's tongue includes damages to a private rancher such as forage loss, cleaning cost, and increased holding cost. These private costs can be measured using market prices. The social cost of hound's tongue includes damages to society such as loss of biodiversity[1], loss of recreation, and cost of soil erosion. However, these social damages are not marketed and therefore, researchers face some difficulties in measuring such damages. Private rancher does not consider the social cost of invasion, when he or she makes decisions on invasive plant management (van Kooten and Bulte, 2000; Grimsrud et al., 2008). This neglect of social cost leads to a socially inefficient level of controlling invasive plants species in rangelands. Due to the divergence between the private and social costs, a privately optimal level of control related to hound's tongue always remains below the socially optimal level (see Figure1). Eventually, such a situation leads to the deterioration of the economic wellbeing of the wider society. Therefore, how to narrow the gap between the private and social costs or internalizing the externalities of biological invasion becomes an important policy problem for resource managers and policy makers.

Figure 1 shows how a divergence between the private and social costs of invasion leads to a socially inefficient level of control on invasive plant species. The curves MC_P and MB_P show the private costs of invasion and private benefits of controlling hound's tongue in rangelands, respectively.

[1] Biodiversity means species diversity and species richness. Biodiversity is not evenly distributed. It varies across the globe as well as within the region.

Figure 1. Divergence between Private and Social Costs in Controlling Invasive Plants



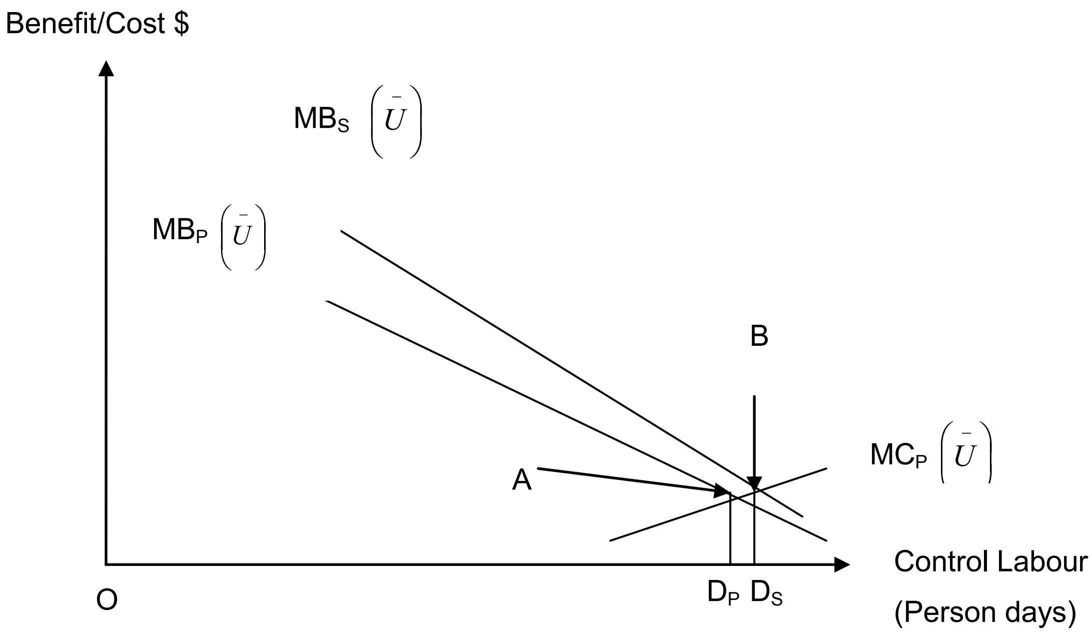
Note: The vertical axis shows cost and benefit of control and the horizontal axis demonstrates the number of person days allocated for controlling hound`s tongue. $MC_p$ and $MB_p$ curves represent the marginal private cost and benefit of control, respectively. $MB_s$ curve represents the marginal social benefits of control. $OD_p$ and $OD_s$ represent the privately and socially allocated labour for controlling hound`s tongue, respectively. OP_0 gives marginal private cost and benefit at the private equilibrium. OP_1 represents the marginal private cost and marginal social benefit at the social equilibrium.

In this figure, I assume that treated land area is the output of a production function. Hound’s tongue U_t is a fixed factor input in the production function. The quantity of labour is a variable input in the production function, and the representative rancher allocates labour to treat the hound’s tongue infested land area in his or her rangeland. Point A shows a competitive private equilibrium where MC_P intersects with MB_P. At the competitive equilibrium, a representative rancher does not consider the social profits from controlling hound’s tongue in the rangeland. Based on the marginal private costs and benefits, such a rancher determines the treated area of rangeland at point A. At this point the rancher allocates OD_P person days of labour for controlling hound's tongue in the rangeland. Point A is a private equilibrium because at this point the rancher maximizes private profits.

Point "B" in Figure 1 shows a social equilibrium where the marginal private cost is equal to the marginal social benefits. According to Figure 1, the socially optimal level of control (OD_s) is greater than the privately optimal level of control (OD_p). Therefore, a divergence between the private and social costs creates an inefficiency of resource allocation in controlling invasive plant species in the rangeland. However, there may not be such an interior solution for the privately competitive equilibrium in controlling hound's tongue in the rangeland. In some cases, where the rancher attempts to reach nearly a complete control of hound's tongue in the rangeland, a private rancher may reach towards a corner solution. Figure 2 illustrates such a case that represents a corner solution in controlling hound's tongue.

In Figure 2, point A shows a solution to the privately competitive equilibrium and point B gives a solution to the socially optimal level of control that is qualitatively the same. According to Figure 2, there is no considerable difference between these two levels of equilibria. In this study, I examine the impact of divergence between the private and social costs on the economic welfare loss to ranchers in BC and its' implications for invasive plant management in rangelands. Furthermore, I test whether there is an interior solution or corner solution for the representative rancher's invasive plant management problem by developing a bio-economic model. In doing so, I will provide a theoretical foundation for valuing the economic impacts of biological invasion on ranchers in the next section.

Figure 2. Divergence between Private and Social Costs in Controlling Invasive Plants with Corner Solution



Note: In Figure 2, the vertical axis represents the marginal costs and benefits of control. The horizontal axis shows the number of person days used for controlling hound`s tongue. Curves $MC_p$ and $MB_p$ show the private marginal costs and benefits of control, respectively. $MB_s$ shows the social marginal benefits of control. $OD_p$ shows the number of person days allocated for controlling hound`s tongue at the private equilibrium. OD_s represents the number of person days allocated for controlling hound`s tongue at the social equilibrium.

5. Measuring the Economic Impact of Invading Hound's Tongue

The environment can play a significant role in influencing the production of market goods. It may serve as an input into a household's production of goods for the personal consumption (Freeman, 1993; McConnell and Bockstael, 2005). A change in environmental quality may lead to an increase or a decrease in production, and would alter the effective demand for non-environmental factor inputs. The impacts of environmental quality change on household production can be modelled using a production function approach as long as the prices of these factor inputs are not affected by the environmental quality change (Freeman, 1991; Freeman, 1993; McConnell and Bockstael, 2005). This approach is known as the production function approach to non-market valuation. In this study, I use the production function approach to measure the economic impacts of invading hound's tongue in the rangelands of BC.

The invasion of rangelands by hound's tongue creates inter-specific competition with native grass species in rangelands. Hound's tongue competes with native grass species for nutrients, water, and space. This inter-specific competition may lead to a decline in the forage production in rangelands, and therefore would reduce the forage available for cattle consumption (Upadhyaya and Cranston, 1991; De Clerck Floate, 1997). Since a reduction in forage production leads to a decline in the economic profits of ranching enterprise, ranchers attempt to control invasive plant species in rangelands. To control invasive plant species, ranchers use different control techniques such as mechanical control, biological control, and pesticides use (De Clerck Floate, 1997; De Clerck Floate et al., 2005). In this study, I assume that a representative rancher pulls hound's tongue, which is a form of mechanical control. Despite such control effort, inter-specific competition may lead to establish invasive plant species as a pest in the new habitat so that the two species coexist in the same habitat (Barbier, 2001). I am interested in measuring the negative impacts of such inter-specific competition between the invader (i.e. hound's tongue) and the economically valuable grass species.

In doing so, I give attention to measuring the post-invasion profits from the commercially valuable species, namely livestock. I assume that the post-invasion profits are greater than zero but smaller than the pre-invasion level (Barbier, 2001; Knowler and Barbier, 2005). The outbreak of hound's tongue in the rangelands of BC represents a case in point: hound's tongue leads to a decline in the profitability of livestock production but does not eliminate all profits.

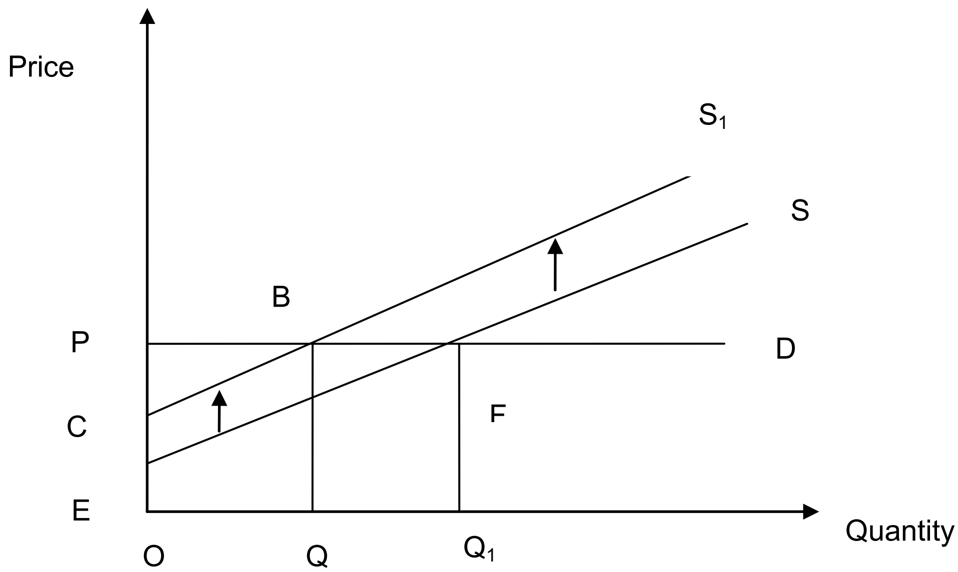
The economic costs of invasion by an exotic species such as hound's tongue consist of private and social costs. I consider the forage losses, supplementary feeding costs, and control costs as the private costs of invasion because such costs affect the economic wellbeing of individual ranchers. Furthermore, I consider the additional social costs from damages to recreation opportunities and from soil erosion due to the invasion because they may create adverse impacts on the economic wellbeing more generally (i.e. non-ranchers). In this bio-economic modeling, I first consider only the private costs and then both the private and social costs of invasion in developing optimal management strategies.

The economic welfare loss resulting from an invasion can be measured as a non-marginal change in producer surplus[2]. In doing so, the producer surplus of the ranching enterprise can be measured with and without biological invasion. In this analysis, I assume that the representative ranching enterprise is a price taker in the beef market so that the rancher faces a demand curve that is perfectly elastic. In the more general case, the demand curve is downward sloping. Figure 3 gives an illustration for measuring the non-marginal change in the economic welfare loss due to the invasion of hound's tongue in the rangelands. "D" and "S" represent perfectly elastic demand and upward sloping supply curves in the beef market.

Point "F" in Figure 3 shows the equilibrium in the beef market before a decline in forage productivity due to biological invasion. The triangles EFP represent the producer surplus before the biological invasion. As a result of biological invasion, there is an upward shift of the beef supply curve. The new market equilibrium is point "B". Triangle BCP represents the producer surplus after the biological invasion. The area of BCEF shows a non-marginal welfare change from biological invasion. This non-marginal change in economic welfare (BCEF) includes both consumer and producer surpluses. In my analysis, the economic damages from the invasion of hound's tongue only include the producer surplus because I assume that a representative rancher is a price taker in the beef market.

[2] The producer surplus is the difference between total revenue (TR) and total variable cost (TVC) (Π=TR-TVC) of the ranching enterprise. In the short run, the producer surplus is also equal to the quasi rent =TR-TVC (total variable cost)= Π+TFC (total fixed cost).

Figure 3. Non-Marginal Change in Economic Welfare



Note: In Figure 3, the vertical axis shows the price of beef and the horizontal axis shows the quantity of beef. D and S represent the demand for and supply of beef before the invasion of hound`s tongue. $S_1$ shows the supply of beef after the invasion of hound`s tongue. OP represents the equilibrium price. OQ_1 and OQ represent the pre-and post-invasion equilibrium quantity of beef, respectively.

Following Ellis and Fisher (1987), the difference between the discounted pre and post invasion producer surpluses gives the economic welfare loss to the representative rancher and society due to the invasion of hound's tongue in the rangeland. Assuming an infinite time frame and optimal management, the private and social welfare losses are given in equation (1) and (2), respectively:

$$\Delta W_p = W_a - W_b \tag{1}$$

$$\Delta W_s = W_a - W_c \tag{2}$$

Where W_a is the discounted pre-invasion producer surplus and W_b is the post-invasion producer surplus that is measured as a difference between the discounted revenue and private costs. W_c is the post invasion producer surplus, which is the difference between discounted revenue and social costs. In the next section, I describe a bio-economic model that captures these considerations in valuing the economic damages from invasive plant species in rangelands

6. Bio-economic Model of a Representative Ranching Enterprise

In this section, I describe the components of a bio-economic model that represent the behaviour of a rancher who has a rangeland infested by an exotic plant (i.e. hound's tongue). I first describe the characteristics of a representative ranch and the basic assumptions governing its operation under the presence of the invader. Second, in this section, I describe seasonal and annual components of the model that will be used to present the representative rancher's problem in an optimal control framework.

6.1. Modelling Assumptions: Ranch Operations in British Columbia

This bio-economic model describes the short-run operation of a representative ranching enterprise. It assumes that the representative ranching enterprise retains some cow-calf units at the end of the previous annual grazing season, and grazes them at the beginning of the current annual grazing season on rangeland leased by the rancher. The grazing period is six months and the rancher sells most livestock at the end of this period, saving some for reproduction. As noted earlier, I assume that the rancher is a price taker in the beef market, facing a perfectly elastic demand curve for beef.

Hound's tongue's impact on profitability may be manifested in three ways: (i) the rancher may maintain his or her fixed stocking rate but accept a reduced weight gain over the grazing season, (ii) the rancher may choose to purchase supplementary feed to make up the forage “gap”, or (iii) the rancher can treat hound’s tongue to prevent a deterioration of the quality of the rangeland. In this model, I assume that the rancher maintains a fixed herd size throughout the grazing season and does not adjust the stocking rate to take into account the invasion of hound’s tongue but purchases supplementary feed and takes into account the possibility of treating the invaded area to reduce the loss in productivity in the rangeland.[3]

Therefore, the producer’s problem is to maximize the ranch enterprise profit subject to the growth in the land area infested by hound’s tongue. The control variable of the model is the quantity of labour that is used to pull hound’s tongue, and the state variable of the model is the area invaded by hound’s tongue at time *t*. The management problem is to derive the steady state optimal values for the quantity of labour that is required for pulling hound’s tongue and the land area infested by hound’s tongue as the invasion proceeds over time, but these are linked. The rancher can decrease the labour requirement for pulling by purchasing supplementary feed which is optimally determined as a residual. An increase in rangeland productivity resulting from treatment causes an increase in forage supply and reduces the purchases of supplementary feed. These changes in economic and ecological variables due to the invasion of hound’s tongue are related to the private cost of invasion in the bio-economic model. In addition to the private cost of invasion described above, the invasion by hound’s tongue creates substantial damages to the wider society. The optimal control problem related to this additional problem is to maximize social welfare subject to the additional cost imposed on society by the invasion and the invasion dynamics associated with hound’s tongue.

6.2. **Seasonal Components of the Model**

I assume that the total stock consists of X number of cows and N number of calves during the grazing season in year t. At the end of the grazing season, a representative rancher sells N number of calves, and holds X number of cows over the winter season for reproduction. In addition, I assume that off take N is a proportion of X

[3] Field interviews indicated that this strategy is often adopted.

and can be written as vX. Thus, $N \leq X$. In this bio-economic model, L represents the fixed area of rangeland, which includes rented and deeded grazing areas measured in hectares. Also, z is the grazing productivity measured in hectares required per cow calf unit per grazing season. Therefore, the sustainability condition for rangeland is:

$$X = \frac{L}{z} \tag{3}$$

Equation (3) indicates that to maintain the sustainability of rangeland, total cow calf units should be smaller or equal to the grazing capacity of rangeland. I assume that this sustainability condition serves as the fixed (and maximum) herd size, and that the rancher's decision problem is to meet forage requirements so as to maximize profit. Once the range degrades, livestock need not depend exclusively on forage obtained from the rangeland because this can be supplemented with purchased feed or the rancher can treat invaded areas.

I assume that the mortality rate of cows and calves during the grazing season is negligible. Therefore, the total livestock sales per season are simply N.[4] Total sales include hound's tongue infested animals N^i and non-infested animals N^{ni}, or $N^{ni} = N - N^i$. The number of infested animals is a function of off take N, the land area currently infested with hound's tongue U_t and the fixed rangeland area L:

$$N^i = f(U_t, N, L), \quad f_U > 0, f_N > 0 \tag{4}$$

I assume that the total number of infested animals is a proportion of the off take N and the proportion of land area infested by hound's tongue U_t/L. According to this assumption, I can specify the total number of hound's tongue infested animals in (4) as:

$$N^i = N\left(\frac{U_t}{L}\right) \tag{5}$$

4 I make this assumption, common to many bio-economic models (Clark, 1990), to avoid cluttering the model, although ranchers report mortality of a few percent in most instances. However, including this would not change our results.

To meet the forage requirement the rancher can graze their livestock on the fixed rangeland, as described above, and they can purchase supplementary forage. Assuming the feed demand per animal for the grazing season is *g*, measured in pounds, the total required forage is *gX*. Due to the infestation of hound's tongue in rangeland, the amount of grazing land area decreases. As a result, the amount of forage that can be met via grazing is $g\left(\frac{L-U_t}{z}\right)$. The residual feed demand *R* must be met from purchased forage and is expressed as:

$$R = g\left(\frac{U_t}{z}\right) \tag{6}$$

6.3. **Annual Component of the Model**

The annual component of the model comprises the year-to-year growth relationship governing the expansion of the invader (hound's tongue) through the fixed rangeland area and treatment to control and limit this expansion. Following Shigesada and Kawasaki (1997), I assume that the annual growth of the invader is exponential, and that this can be modelled using the logistic growth function. The rancher attempts to control the hound's tongue infested land area, resulting in an annual treated area T_t.

Based on the discrete logistic growth model, the annual increment in area invaded is:

$$U_{t+1} - U_t = rU_t\left(1-\frac{U_t}{L}\right) - T_t \tag{7}$$

where *r* is the biological intrinsic growth rate of hound's tongue.

To control hound's tongue, the rancher pulls hound's tongue at the beginning of the grazing season each year. The rancher spends D_t person days for pulling hound's tongue, and I assume that the output from this effort is subject to an asymptotic limit equal to U_t and diminishing returns, given the increasing difficulty and search time involved in locating plants to pull as treatment proceeds. A simple production function that captures these characteristics is:

$$T(D_t) = U_t\left(1 - e^{-\beta D_t}\right), \quad \beta<0 \tag{8}$$

Where $0 \leq T_t \leq U_t$, and as D_t approaches infinity, T_t approaches U_t. Thus, the treatment function is concave in D_t . In the next section, I present a ranchers' management problem in an optimal control framework.

7. Optimal Management of Invasive Plant Species in Rangelands

The above relationships are introduced into a standard optimization framework describing the rancher's management problem from which I can deduce the optimal control strategy for the representative ranching operation. First, I analyze the steady state equilibrium considering only the private cost of invasion by hound's tongue[5]. Second, I extend this analysis by taking into account additional social costs of invasion. Third, I consider the optimal labour allocation related to a private rancher, who controls hound's tongue in his or her own private rangeland as well as in the neighbouring rangeland.

7.1. Private Cost of Invasion and Steady State Equilibrium

I begin by describing the rancher's profit relationship, which is composed of revenue from livestock sales at the end of the grazing season less purchase of

[5] At the steady state equilibrium, the growth rate of a particular resource with time is equal to zero. At this point the first partial derivative of the resource growth with respect to time is equal to zero

supplementary feed, grazing rental, trucking and marketing cost, veterinary cost and labour hired for invasive plant control. I assume that the net selling price p_m of animals can be obtained by subtracting trucking and marketing costs from the market price. Thus, the total revenue from livestock sales at the end of grazing season is $p_m N$. If the price per pound of supplementary feed is p_r, and the total supplementary feed requirement for the grazing season is R_t, the cost of supplementary feed requirement for the grazing season is $p_r R_{t,}$, assuming all the feed requirements are purchased. The total forage available for the grazing season is $g\frac{L-U_t}{z}$ and the unit rental price per hectare of grazing land is p_a. Thus, the rental cost of forage available for the grazing season is $p_a L$.[6] Finally, I assume a daily wage rate w is paid to the labour for pulling hound's tongue plants from the treatment area T_t. The total labour used to pull hound's tongue annually is D_t and, therefore, the total labour cost for pulling hound's tongue is wD_t. In addition, my focus group interviews showed that a representative rancher has veterinary and supplementary feeding material expenses over the winter season. This cost is introduced to the model as a holding cost. Assuming p_h is the holding cost per cow calf, and the total holding cost is $p_h X$.

Additionally, I assume that the price discount per hound's tongue infested animal under the best option is η. Key informant interviews showed that ranchers follow three options to prevent the reduction in the value of cattle, which are infested with hound's tongue infested cattle: selling infested animals without first cleaning, holding infested animals for a sufficient period to allow natural removal of hound's tongue burrs, and cleaning infested animal before marketing. When ranchers sell hound's tongue infested animals without cleaning, this reduces their market value. If the rancher holds the hound's tongue infested animal to allow natural removal, the ranching enterprise has to bear an extra feed cost, but there may be some increase in the exogenous market price from holding livestock that may partially offset the additional feed cost. If the infested animals are cleaned before marketing, there is an additional cost associated with the cleaning that is born by ranchers. The optimal response to the marketing of infested

[6] I assume that the payment for AUM is made as a fixed rent regardless of the range conditions.AUM is the amount of forage required by an animal unit per month

animals depends on such parameter values. However, my calculation shows that cleaning infested animals is the best option available for the representative ranching enterprise (see Table A.1 in the appendix). Taking these considerations into account, the profit expression for the representative ranching enterprise is:

$$\Pi_p = (p_m - \eta)N^i + p_m(N - N^i) - wD_t - p_a L - p_h X - p_r R_t \tag{9}$$

Substituting (5) and (6) for N^i and R_t respectively and setting μ=g/z, (9) can be rearranged to yield the following discrete time management problem facing the representative ranching enterprise:

$$\underset{D_t}{Max}\, J = \sum_{t=0}^{\infty} \rho^t \left[p_m N - \eta N\left(\frac{U_t}{L}\right) - wD_t - p_h X - p_a L - p_r \mu U_t \right] \tag{10}$$

subject to:

$$U_{t+1} - U_t = rU_t\left(1 - \frac{U_t}{L}\right) - U_t\left(1 - e^{-\beta D_t}\right) \tag{11}$$

where $\rho = \left(\frac{1}{1+\delta}\right)$ is the discount factor and δ is the discount rate.

Setting the objective functional in (10) as *V(.)* and taking D_t as the control variable and U_t as the state variable, the discrete current value Hamiltonian for this management problem is:

$$H_C = V(.) + \rho\lambda_{t+1}\left[rU_t\left(1 - \frac{U_t}{L}\right) - U_t\left(1 - e^{-\beta D_t}\right)\right] \tag{12}$$

Where, λ_{t+1} is a shadow price of the state variable (hound's tongue) in period *t+1* (Conrad and Clark, 1995). The first component on the right hand side of the Hamiltonian simply shows the short-run profit or producer surplus of the representative ranching enterprise in time t, based on the current hound's tongue infested land area and current policy decision taken by the rancher on the treatment of hound's tongue infestation. The second component of equation (12) indicates the rate of change of hound's tongue infestation *(U_{t+1}-U_t)*, corresponding to the policy decision on treatment *(D_t)*, converted into a discounted monetary value. Since the objective of the ranching enterprise is profit maximization, the second term represents the future profit effect of treatment D_t.

The first order conditions for this management problem can be written as:

$$\frac{\partial H_C}{\partial D_t} = -w - \rho\lambda_{t+1}U_t\beta e^{-\beta D_t} = 0 \text{ or } \quad w = -\rho\lambda_{t+1}\left(\beta U_t e^{-\beta D_t}\right) \tag{13a}$$

$$-\frac{\partial H_C}{\partial U_t} = \frac{\eta N}{L} + \mu p_r - \rho\lambda_{t+1}\left[r\left(1-\frac{U_t}{L}\right) - \frac{rU_t}{L} - 1 + e^{(-\beta D_t)}\right] = \rho\lambda_{t+1} - \lambda_t \tag{13b}$$

$$\frac{\partial H_C}{\partial \rho\lambda_{t+1}} = rU_t - r\frac{U_t^2}{L} - U_t\left(1 - e^{-\beta D_t}\right) = U_{t+1} - U_t \tag{13c}$$

Condition (13a) indicates that the marginal cost of treatment or wage rate *w* should be equal to the value of marginal benefits of treating hound's tongue. The sign of the marginal value term becomes negative because the representative ranching enterprise has to bear the cost of treating hound's tongue $\lambda_{t+1}<0$. In the dynamic context, the term $\rho\lambda_{t+1}$ ($\partial T_t(.)/\partial D_t$) explicitly reflects the influence of D_t on the change in the state variable through the treatment activity. Since an increase in D_t reduces the land area infested by hound's tongue, this term reflects the inter-temporal benefits of treatment.

At the steady state $\lambda_{t+1}=\lambda_t=\lambda^*$, and $U_{t+1}=U_t=U^*$ and therefore first order condition (13a) becomes:

$$\lambda^* = -\frac{w}{\rho\beta U^* e^{-\beta D^*}} \tag{14}$$

Equation (14) calculates the shadow price of the state variable *(U_t)* at the steady state. Since the infestation by hound's tongue generates a welfare loss to ranchers, the shadow price of hound's tongue measures the marginal social cost of hound's tongue.

At the steady state equilibrium, (13c) can be used to solve for D^*:

$$D^* = -\frac{\ln\left(\frac{-rL + rU^* + L}{L}\right)}{\beta} \tag{15}$$

Equation (15) shows the steady state optimal value of labour allocation for treating hound's tongue in the representative rangeland. Substituting equation (14) and (15) into (13b), and evaluating it (13b) at the steady state, I can derive the so-called golden rule of renewable resource management for this problem (Huffaker and James, 1991)[7]:

$$\delta = -\frac{\left[\frac{\eta N}{L} + \mu p_R\right]}{w\beta U^* e^{-\beta D^*}} - \left[r\left(1 - \frac{U^*}{L}\right) - \frac{rU^*}{L} - 1 + e^{-\beta D^*}\right] \tag{16}$$

Numerical estimates for the steady state solutions U^* and D^* can be derived by substituting (15) into (16) and then solving the resulting implicit equation. These solutions provide the steady state equilibrium related to the representative rancher who takes into account only the private cost of invasion. As noted earlier, the hound's tongue invasion creates significant social costs to the wider society. To implement economically efficient and socially optimal policies for controlling invasive plant species in rangelands, it is necessary to account for the social cost of invasion in valuing the economic damages from such plant species. In the next section, I describe the impact of such invasion on the steady state values of the control variable D_t and the state variable U_t.

[7] For optimality, the rate of return on the resource (marginal growth rate+ marginal stock effect) when maintaining stock at the steady state must equal to the discount rate, the latter representing the rate of return on investment in other sectors of the economy (Conrad, 2010).

7.2. **Social Cost of Invasion and Steady State Equilibrium**

My previous optimal control management problem only takes into account the private cost of invasion such as forage losses, control costs, and supplementary feeding costs. Therefore, from a social perspective such an analysis may under estimate the full economic damages from hound's tongue. In addition, the private steady state equilibrium does not offer socially optimal outcomes for the invasive plant management problem. Previous research studies showed that invasive plant species create a substantial amount of social or non-market damages to the wider society (RNT, 2002; Colautti et al., 2006; Frid, et al., 2008). These social costs include loss of biodiversity loss, recreation opportunities, increasing offsite soil erosion, and loss of forage and degradation of habitat for non-livestock wildlife. To provide appropriate policy strategies for invasive plant management in the rangelands, it is necessary to consider the social costs of biological invasion in measuring the economic welfare losses to ranchers.

To measure the social damages from hound's tongue, I express damages as a product of the total area invaded by hound's tongue, $U_{t,}$ and the average social damage per hectare invaded, c. Thus, the total social damages at time, t, are cU_t with c>0. Assuming an infinite time horizon and a constant average cost per hectare over time, the present value of total non-private costs from invasion are given as follows:

$$\sum_{t=0}^{\infty} \rho^t c U_t \tag{17}$$

When the representative rancher considers both the private and social costs the profit equation is:

$$\Pi_S = p_m N - \eta N\left(\frac{U_t}{L}\right) - wD_t - p_a L - p_h X - p_r \mu U_t - cU_t \tag{18}$$

The objective function related to the above social welfare management problem is given as follows:

$$\underset{D_t}{Max}J = \sum_{t=0}^{\infty} \rho^t \left[\left(p_m N - \eta N\left(\frac{U_t}{L}\right) - wD_t - p_a L - p_h X - U_t(\mu p_r + c) \right) \right] \quad (19)$$

subject to:

$$U_{t+1} - U_t = rU_t\left(1 - \frac{U_t}{L}\right) - \left[U_t\left(1 - e^{-\beta D_t}\right)\right] \quad (20)$$

$\rho = \left(\frac{1}{1+\delta}\right)$ *is the discount factor and* δ *is the discount rate.*

Setting the objective functional in (19) as $Z(.)$ and taking D_t and U_t as the control and state variables, respectively, the discrete current value Hamiltonian for this management problem is:

$$H^{/} = Z(.) + \rho\lambda_{t+1}\left[rU_t\left(1 - \frac{U_t}{L}\right) - U_t\left(1 - e^{-\beta D_t}\right) \right] \quad (21)$$

The first order condition for this management problem can be written as follows:

$$\frac{\partial H^{/}}{\partial D_t} = -w - \rho\lambda_{t+1} U_t \beta e^{-\beta D_t} = 0 \quad (22a)$$

$$-\frac{\partial H^{/}}{\partial U_t} = \frac{\eta N}{L} + (\mu p_r + c) - \rho\lambda_{t+1}\left[r\left(1 - \frac{U_t}{L}\right) - \frac{rU_t}{L} - 1 + e^{-\beta D_t} \right] = \rho\lambda_{t+1} - \lambda_t \quad (22b)$$

$$\frac{\partial H^{/}}{\partial \rho\lambda_{t+1}} = rU_t - r\frac{U_t^2}{L} - \left(U_t\left(1 - e^{-\beta D_t}\right)\right) = U_{t+1} - U_t \quad (22c)$$

At the steady state $\lambda_{t+1} = \lambda_t = \lambda^*$ and $U_{t+1} = U_t = U^*$ and from (22a) we get:

$$\lambda^* = -\frac{w}{\rho\beta U^* e^{-\beta D^*}} \tag{23}$$

and from (22c):

$$D^* = \frac{-\ln\left(\frac{-rL + rU^* + L}{L}\right)}{\beta} \tag{24}$$

The golden rule related to this social welfare management problem is:

$$\delta = -\frac{\left(\frac{\eta N}{L} + (\mu p_r + c)\right)}{w\beta U^* e^{-\beta D^*}} - \left[r\left(1 - \frac{U^*}{L}\right) - \frac{rU^*}{L} - 1 + e^{-\beta D^*}\right] \tag{25}$$

This is the expression for the modified golden rule for the social welfare management problem. This golden rule expression differs from the golden rule expression in (16) due to the parameter *c* that captures the social cost of invasion. Since the social cost *c* takes a positive value in this expression, the socially optimal steady state *D** is larger than the private steady state *D** in (16). This result indicates that when the representative rancher considers the social cost of invasion, he or she tends to treat more infested land area compared to the land area treated when considering private cost only. Therefore, the socially optimal steady state U^* is greater than the privately optimal steady state U^*.

In addition, my key informant interviews showed that the invasion of hound's tongue in neighbouring public rangelands creates negative externalities nearby. Therefore, private ranchers may have interests in controlling hound's tongue not only in his or her own private rangeland, but also in the neighbouring public rangeland. Such behaviour of a private rancher may have important policy implications for invasive plant management. Therefore, in the next section, I discuss how such behaviour affects the steady state equilibrium in the level of infestation, labour allocation, and the economic welfare losses to the representative rancher.

7.3. **Controlling Hound's Tongue in the Neighbouring Rangeland: Private Perspective**

In this section, I attempt to analyze the invasive plant control behaviour of the representative ranching enterprise on the steady state values of control and state variables, when the rancher can allocate labour for pulling hound's tongue in the neighbouring rangeland. This model also analyzes the impact of changes in such variables on the economic welfare losses to ranchers. In doing so, I consider a private rancher who controls hound's tongue in adjacent public rangelands (i.e. Crown land). For the mathematical tractability of the model, I assume that the relevant area of public rangeland is equal to the size of the representative rancher's rangeland. These public rangelands are also infested by hound's tongue, and such infestation adversely affects the forage productivity in both rangeland areas. I also assume that the proportion of infestation is equal in two plots of rangelands, namely, representative and neighbouring. Furthermore, the representative rancher attempts to control hound's tongue in their own rangeland independently but can control the invader in adjacent rangeland too. In doing so, he/she only considers the private cost of invasion in decision making on ranching operations.

According to the theoretical and empirical evidence from ecology, many factors such as mammal, birds, winds, and humans affect the seed dispersal in rangelands (Sinclair, et al., 2006). However, I assume that the impact of seed dispersal from the neighbouring public rangeland on the infestation in the representative rangeland φ is equal to the impact of seed dispersal from the representative rangeland on the infestation in the neighbouring rangeland ω. This means that there is an equal dispersal in both directions. Since φ and ω are proportions of total stock of hound's tongue in each category of land, the values of these parameters are less than one. However, infestation of one plot of land positively affects the level of infestation of other plot of land. Therefore, values of φ and ω are positive. Although these are simplifying assumptions for seed dispersal of invasive plant species, they allow me to keep the bio-economic model tractable.

My key informant interview showed that the invasion of hound's tongue in the neighbouring rangelands leads to increase the spread of hound's tongue and expands the infested land area in the private rangeland. An increase in infested land area reduces the forage productivity, and it decreases the economic welfare of ranching enterprise. Therefore, the profit-maximizing ranching enterprise allocates labour not only for controlling hound's tongue in his or her own rangeland, but also in the neighbouring public rangeland. After taking into account such considerations, hound's tongue growth in two neighbouring rangeland is given as follows:

$$U_{t+1} - U_t = r(U_t + \varphi Y_t)\left(1 - \frac{U_t}{L}\right) - U_t\left(1 - e^{-\beta D_t}\right) \quad 0 \leq \varphi \leq 1 \tag{26}$$

$$Y_{t+1} - Y_t = r(Y_t + \omega U_t)\left(1 - \frac{Y_t}{M}\right) - Y_t\left(1 - e^{-\beta E_t}\right) \quad 0 \leq \omega \leq 1 \tag{27}$$

Where U_t =Infested land area of the representative rangeland (hectares)

Y_t = Infested land area of the neighbouring rangeland (hectares)

L = Total area of representative rangeland (hectares)

M=Total area of neighbouring rangeland (hectares)

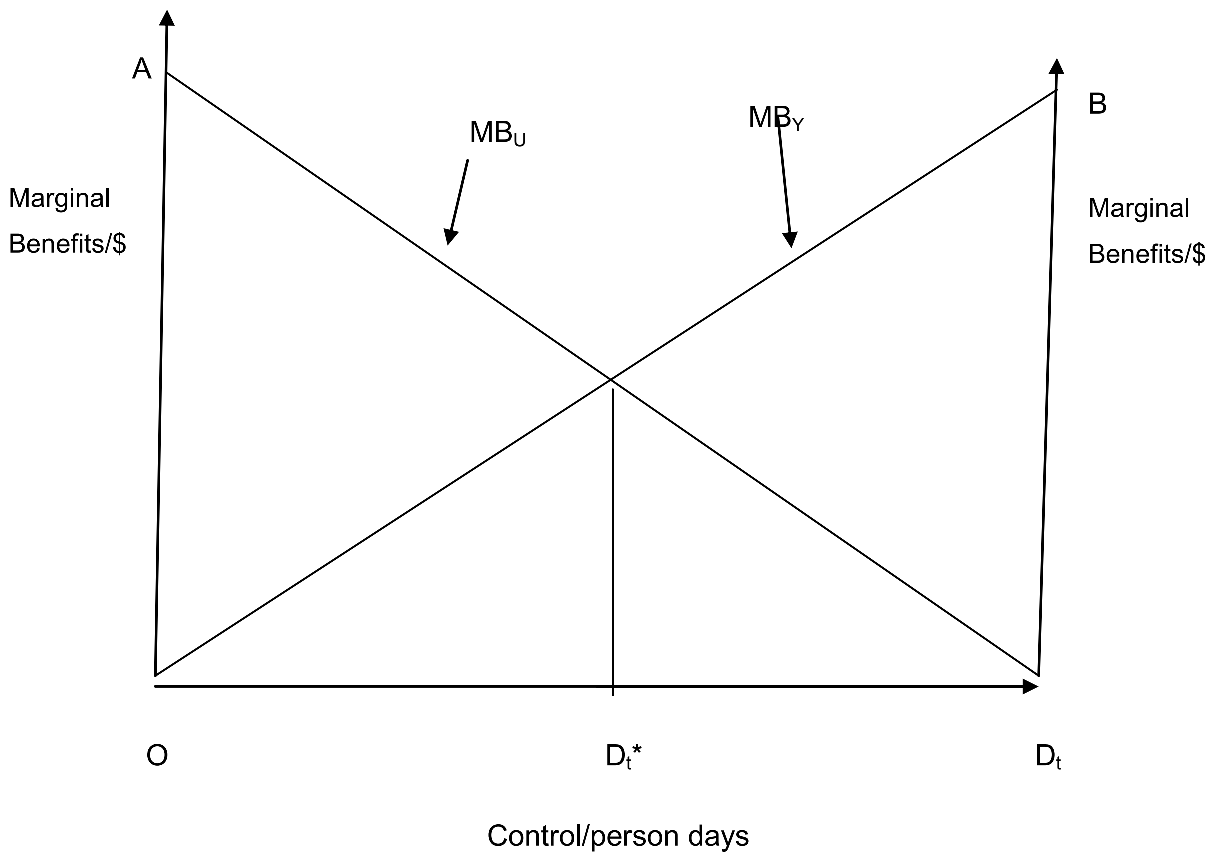
D_t = Labour for pulling hound's tongue in the representative rangeland (person days)

E_t = Labour for pulling hound's tongue in the neighbouring rangeland (person days)

Equation (26) represents the growth of hound's tongue in the representative rangeland, and equation (27) represents the growth of hound's tongue in the neighbouring public rangeland. According to economic theory, a profit-maximising ranching enterprise allocates labour for controlling hound's tongue in the neighbouring public rangeland to the point where the marginal benefits of controlling hound's tongue in his or her own rangeland is equal to the marginal benefits from controlling hound's tongue in the neighbouring rangeland. Figure 4 shows such labour allocation equilibrium in controlling hound's tongue in the neighbouring rangeland.

In Figure 4, OD_t shows the quantity of labour available for controlling hound's tongue in his or her own rangeland and the neighbouring public rangeland. MB_U and MB_Y show the marginal benefits of controlling hound's tongue in his or her own rangeland and in the neighbouring public rangeland, respectively. These curves show that when control increases, the marginal benefits from control decrease. As shown in the previous analysis, I assume that a representative ranching enterprise maximises profits and operates in the perfectly competitive market. Thus, he or she allocates labour for controlling hound's tongue to the point where the marginal benefits from controlling hound's tongue in his or her own rangeland equals to the marginal benefits from controlling hound's tongue in the neighbouring rangeland.

Figure 4. Controlling Hound's Tongue in the Public Neighbouring Rangeland



Note: In Figure 4, OA shows the benefits of controlling hound's tongue in the representative rangeland. MB_U represents the marginal benefits of controlling hound's tongue in the representative rangeland. D_tB represents the benefits of control in the neighbouring rangeland. OD_t shows the total amount of labour available for controlling hound's tongue in both representative and public rangeland. MB_y gives the marginal benefits of control in the neighbouring rangeland.

In Figure 4, D_t* is the equilibrium point of the labour allocation. At this equilibrium point, a representative rancher allocates the OD_t* and D_tD_t* amount of labour for controlling hound's tongue in his or her own rangeland and the neighbouring rangeland respectively. However, this labour allocation decision affects the steady state values of control and state variables in the bio-economic model and thereby the economic welfare of the representative ranching enterprise. Therefore, to take policy decisions on invasive plant management, it is necessary to understand the impacts of labour allocation between controlling hound's tongue in his or her own rangeland and the neighbouring public rangeland on the economic welfare of ranchers. In Particular, economic theory indicates that a private rancher is not willing to control invasive plant species in neighbouring public rangelands because they are not interested in social benefits of control. However, my focus group interviews showed that this is not the case related to the invasive plant management in rangelands in Okanagan. If there are sufficient private payoffs, private ranchers are interested in controlling invasive plant species in neighbouring public rangelands because it may improve the economic welfare of such ranchers. Therefore, in this analysis, I attempt to examine the impact of such behaviour on the steady state equilibrium and its implications for invasive plant management.

By taking into account these considerations, the profit expression for the ranching enterprise is:

$$\Pi_{np} = (p_m - \eta)N^i + p_m(N - N^i) - w(D_t + E_t) - p_h X - p_a L - p_r \mu U_t \tag{28}$$

The discrete time management problem facing the representative ranching enterprise is:

$$\underset{D_t, E_t}{Max}\, J = \sum_{t=0}^{\infty} \rho^t \left[p_m N - \eta N\left(\frac{U_t}{L}\right) - w(D_t + E_t) - p_h X - p_a L - p_r \mu U_t \right] \tag{29}$$

Subject to:

$$U_{t+1} - U_t = r(U_t + \varphi Y_t)\left(1 - \frac{U_t}{L}\right) - U_t\left(1 - e^{-\beta D_t}\right) \qquad 0 \le \varphi \le 1; \tag{30}$$

$$Y_{t+1} - Y_t = r(Y_t + \omega U_t)\left(1 - \frac{Y_t}{M}\right) - Y_t\left(1 - e^{-\beta E_t}\right) \qquad 0 \le \omega \le 1; \tag{31}$$

The current value of Hamiltonian for this optimal control problem is given by

$$H_c^{/} = V(.) + \rho\lambda_{t+1}\left[r(U_t + \varphi Y_t)\left(1 - \frac{U_t}{L}\right) - U_t\left(1 - e^{-\beta D_t}\right)\right] +$$
$$\rho\Omega_{t+1}\left[r(Y_t - \omega U_t)\left(1 - \frac{Y_t}{M}\right) - Y_t\left(1 - e^{-\beta E_t}\right)\right] \tag{32}$$

The first order conditions for this management problem are:

$$\frac{\partial H_c^{/}}{\partial D_t} = -w + \rho\lambda_{t=1} U\beta e^{-\beta D_t} = 0 \quad \text{or} \quad w = -\rho\lambda_{t+1} U\beta e^{-\beta D_t} \tag{33a}$$

$$-\frac{\partial H_c^{/}}{\partial U_t} = \frac{\eta N}{L} + \mu p_r - \rho\lambda_{t+1}\left[r - \frac{2rU_t}{L} - \frac{\varphi r Y_t}{L} - 1 + e^{-\beta D_t}\right] = \rho\lambda_{t+1} - \lambda_t \tag{33b}$$

$$\frac{\partial H_c^{/}}{\partial \rho\lambda_{t+1}} = r(U_t + \varphi Y_t)\left(1 - \frac{U_t}{L}\right) - U_t\left(1 - e^{-\beta D_t}\right) = U_{t+1} - U_t \tag{33c}$$

$$\frac{\partial H_c^{/}}{\partial E_t} = -w + \rho\Omega_{t+1} Y_t \beta e^{-\beta E_t} = 0 \quad \text{or} \quad w = -\rho\Omega_{t+1} Y_t \beta e^{-\beta E_t} \tag{34a}$$

$$-\frac{\partial H_c^{/}}{\partial Y_t} = \frac{\eta N_t}{M} - \mu p_r - \rho\Omega_{t+1}\left[r - \frac{2rY_t}{M} - \frac{\omega r U_t}{M} - 1 + e^{-\beta E_t}\right] = \rho\Omega_{t+1} - \Omega_t \tag{34b}$$

$$\frac{\partial H_c^{/}}{\partial \rho\Omega_{t+1}} = r(Y_t + \omega U_t)\left(1 - \frac{Y_t}{M}\right) - Y_t\left(1 - e^{-\beta E_t}\right) = Y_{t+1} - Y_t \tag{34c}$$

Equation (33a) and (34a) represent the maximum principle. The terms $\rho\lambda_{t=1} U_t \beta e^{-\beta D_t}$ and $\rho\Omega_{t+1} Y_t \beta e^{-\beta D_t}$ represent the discounted future value of treated land area infested by hound's tongue in his or her own rangeland and in the neighbouring public rangeland, respectively, discounted by back one period. According to equation (33a) and (34a), at the profit-maximization, the wage rate is equal to the value of the marginal productivity of labour (i.e. the discounted future value of treated area of infested land) in controlling hound's tongue in his or her own rangeland and in the neighbouring rangeland.

First order conditions in (33a) and (34a) can be used to derive such equilibrium condition. Since the labour market is perfectly competitive (i.e. a representative rancher can purchase any amount of labour at wage rate w), the equilibrium condition for the optimal control of hound's tongue is $w = -\rho\lambda_{t=1} U\beta e^{-\beta D_t} = -\sigma\Omega_{t+1} Y_t \beta e^{-\beta E_t}$. In addition, these first order conditions can also be used to derive the shadow prices of state variables of the model. For example, at the steady state, $\Omega_t = \Omega_{t+1} = \Omega^*$ and $Y_t = Y_{t=1} = Y^*$. Thus, the shadow price of hound's tongue in the neighbouring rangeland is written as $\Omega^* = \frac{-w}{Y^* \beta e^{-\beta E^*}}$. This expression indicates the economic cost of treatment per hectare of hound's tongue infested land area in the neighbouring rangeland.

Equation (33b) and (34b) are adjoint equations in the bio-economic model. They represent the growth of shadow prices of each state variable in the model. These first order conditions can be used to derive the golden rule for this private welfare management problem when a representative rancher allocates labour for controlling hound's tongue in not only his or her own rangeland but also in the neighbouring rangeland.

State equations or equation of motions (33c) and (34c) show the steady state growth of hound's tongue in his or her own rangeland and in the neighbouring rangeland. According to these equations, steady state growths of hound's tongue in two neighbouring rangelands are equal to the natural growth of hound's tongue minus the treated area of hound's tongue. However, growth functions in these equations are different from the growth function in equation (13c). According to equation (13c), only the stock of hound's tongue in his or her own land affects the growth of hound's tongue in his or her rangeland. Nevertheless, growth functions in equation (33c) and (34c) indicate that the growth of hound's tongue in the representative and neighbouring rangelands is affected not only by the parental stock but also by the hound's tongue stock in each rangeland area. For example, while ϕY_t represents the influence of the hound's tongue stock in the neighbouring rangeland, ωU_t shows the influence of the stock of the representative rangeland on the neighbouring rangeland.

I can derive the optimal steady state solutions for the control and state variables through solving the above equations simultaneously. Such solutions may help policy makers to identify economically efficient and socially optimal invasive plant management policies. Furthermore, in the next section, I analyze the controlling behaviour of the representative rancher who considers such social damages from hound's tongue in the neighbouring rangeland.

7.4. Controlling Hound's Tongue in the Neighbouring Rangeland: Social Perspective

As mentioned in the introduction, biological invasion generates both private and social costs and thereby creates welfare losses to the wider society. In this section, I assume that a representative rancher allocates labour for controlling hound's tongue in the neighbouring rangelands, and he or she considers the social cost of invasion in the production decisions. In taking into account the social cost of invasion, there may be effects on the steady state values of control and state variables and economic welfare losses. From the social point of view, such findings may have important policy implications for invasive plant management. Therefore, in this section, I analyze the impacts of allocation of labour on controlling hound's tongue in the neighbouring rangeland on the social steady state equilibrium. In doing so, a representative rancher's optimization profit expression is:

$$\Pi_{ns} = (p_m - \eta)N^i + p_m(N - N^i) - w(D_t + E_t) - p_h X - p_a L - \mu p_r U_t - cU_t \tag{35}$$

The discrete time management problem facing the representative ranching enterprise, who controls hound's tongue in the neighbouring rangeland is:

$$\underset{D_t E_t}{Max} J = \sum_{t=0}^{\omega} \rho^t \begin{bmatrix} p_m N - \eta N\left(\frac{U_t}{L}\right) - w(D_t + E_t) - p_h X \\ - p_a L - U_t(\mu p_r + c) \end{bmatrix} \tag{36}$$

Subject to:

$$U_{t+1} - U_t = r(U_t + \phi Y_t)\left(1 - \frac{U_t}{L}\right) - U_t\left(1 - e^{-\beta D_t}\right) \qquad 0 \le \phi \le 1; \tag{37}$$

$$Y_{t+1} - Y_t = r(Y_t - \omega U_t)\left(1 - \frac{Y_t}{M}\right) - Y_t\left(1 - e^{-\beta E_t}\right) \qquad 0 \le \omega \le 1; \tag{38}$$

where; φ and ω equal. The current value of Hamiltonian for this optimal control problem is given:

$$H_c^{//} = V(.) + \rho\lambda_{t+1}\left[r(U_t + \phi Y_t)\left(1 - \frac{U_t}{L}\right) - U_t\left(1 - e^{-\beta D_t}\right)\right] + \rho\Omega_{t+1}\left[r(Y_t - \varpi U_t)\left(1 - \frac{Y_t}{M}\right) - Y_t\left(1 - e^{-\beta E_t}\right)\right] \tag{39}$$

The first order conditions for this management problem is shown as follows:

$$\frac{\partial H_c^{//}}{\partial D_t} = -w + \rho\lambda_{t+1}U_t\beta^{-\beta D_t} = 0 \tag{40a}$$

$$-\frac{\partial H_c^{//}}{\partial U_t} = \frac{\eta N}{L} + \mu p_r + c - \rho\lambda_{t+1}\left[r - \frac{2rU_t}{L} - \frac{\phi r Y_t}{L} - 1 + e^{-\beta D_t}\right] = \rho\lambda_{t+1} - \lambda_t \tag{40b}$$

$$\frac{\partial H_c^{//}}{\partial \rho\lambda_{t+1}} = r(U_t + \phi Y_t)\left(1 - \frac{U_t}{L}\right) - U_t\left(1 - e^{-\beta D_t}\right) = U_{t+1} - U_t \tag{40c}$$

$$\frac{\partial H_c^{//}}{\partial E_t} = -w + \rho\Omega_{t+1}Y_t\beta e^{-\beta E_t} = 0 \tag{41a}$$

$$-\frac{\partial H_c^{//}}{\partial Y_t} = \frac{\eta N}{M} - \mu p_r - \rho\Omega_{t+1}\left[r - \frac{2rY_t}{M} - \frac{\omega r U_t}{M} - 1 + e^{-\beta D_t}\right] = \rho\Omega_{t+1} - \Omega_t \tag{41b}$$

$$\frac{\partial H_c^{//}}{\partial \rho \Omega_{t+1}} = r(Y_t + \omega U_t)\left(1 - \frac{Y_t}{M}\right) - Y_t\left(1 - e^{-\beta E_t}\right) = Y_{t+1} - Y_t \tag{41c}$$

Except equation (40b), economic interpretations of all the above first order conditions are similar to the interpretations of first order conditions in section 7.3. Equation (40b) shows the growth of the shadow price of the state variable U_t. In this social welfare management problem, I consider social damages from hound's tongue. The parameter c in equation (40b) represents the social cost of invasion. Thus, the value of the growth of the shadow price of the state variable in (40b) is greater than the growth of the shadow price of the state variable in (33b). However, equation (40b) and (41b) can be used to derive the golden rule for the social welfare management problem when the representative rancher controls hound's tongue in his and her own rangeland as well as neighbouring private rangeland.

I can derive the optimal steady state solutions for the control and state variables through solving the above equations simultaneously. A comparison of these social steady state values with the private steady state values provides valuable insight for resource managers and policy analysts to come out with better policies for invasive plant management. In addition, changes in controlling behaviour of the representative ranching enterprise affect economic welfare losses. Therefore, in the next section, I carry out a theoretical analysis of the economic welfare losses from hound's tongue in both the private and social welfare cases as well as in the allocation of labour for controlling hound's tongue in the neighbouring rangelands.

7.5. **Welfare Losses from Biological Invasion**

To measure the private and social welfare losses from the invasion of hound's tongue, I compare the pre-invasion profit with the steady state post-invasion profit. The pre-invasion profit is calculated assuming that there is no invasion and the representative rancher operates at the socially optimal level of management with welfare level W_a:

$$W_a = \sum_{t=1}^{\infty} \rho^t \left(p_m N - p_a L - p_h X \right) \tag{42}$$

In contrast, W_b is the discounted post-invasion private producer surplus:

$$W_b = \sum_{t=1}^{\infty} \rho^t \left[p_m N - \eta N \left(\frac{U^{p*}}{L} \right) - w D^{p*} - p_a L - p_r g X - p_h X - p_r \mu U^{p*} \right] \tag{43}$$

Where U^{p^*} and D^{p^*} are optimal values for private steady state equilibria. If I include the social cost of invasion, W_c is the discounted post-invasion expression for social welfare:

$$W_c = \sum_{t=1}^{\infty} \rho^t \left(p_m N - \eta N \left(\frac{U^{S*}}{L} \right) - w D^{S*} - p_a L - p_h X - U^{S*} \left(p_r \mu + c \right) \right) \tag{44}$$

In equation (44), U^{s^*} and D^{s^*} gives optimal solution values for the social steady state equilibrium. Following equation (1) & (2), welfare losses for the private and social cases are given in equation (44a) and (44b), respectively.

$$\Delta W_p = W_a - W_b \tag{44a}$$

$$\Delta W_s = W_a - W_c \tag{44b}$$

If I assume the representative rancher allocates labour for controlling hound's tongue in the neighbouring rangeland and only takes into account the private cost of invasion, the private welfare to the rancher is:

$$W_d = \sum_{t=1}^{\infty} \rho^t \left[p_m N - \eta N \left(\frac{U^{p**}}{L} \right) - w \left[D^{p**} + E^{p**} \right] - p_a L - p_h X - p_r \mu U_t^{p**} \right] \tag{45}$$

In equation (45), $U^{p^{**}}$, $D^{p^{**}}$, and $E^{p^{**}}$ are optimal values for the steady state equilibriums when the rancher allocates labour for controlling hound's tongue in the neighbouring public rangeland. After accounting for the social cost of invasion, the level of social welfare is:

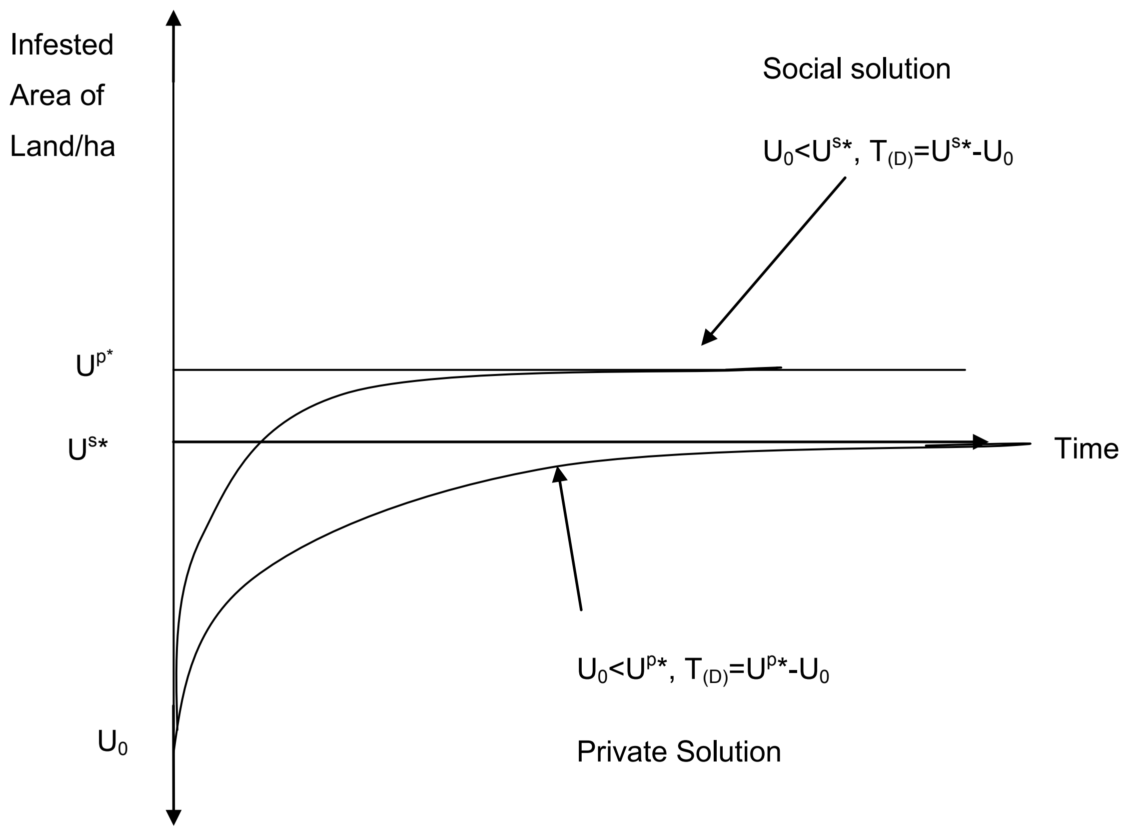
$$W_e = \sum_{t=0}^{\infty} \rho^t \left[\begin{array}{l} p_m N - \eta N \left(\dfrac{U^{S**}}{L} \right) - w\left(D^{S**} + E^{S**}\right) - p_a L - p_h X \\ -U^{S**}\left(\mu p_r + c\right) \end{array} \right] \quad (46)$$

By solving the problems described by equations (43), (44), (45), and (46) with equation (42), I can measure the social welfare losses due to the invasion of hound's tongue in the rangelands of BC. These economic damage estimates can be used to justify the cost of various control programs and to provide policy implications for invasive plant management. In addition, it is very important to identify optimal control and state path of this optimization problem to present optimal policies for invasive plant management. Therefore, in the next section, I elaborate upon the optimal control and state paths for this optimal control problem.

7.6. **Optimal Control Policy for Invasive Plant Management**

The initial formulation of the above optimal control problem provides steady state values for the control variable D_t ,and state variable U_t . The optimal approach path to the steady state level of equilibrium is determined by the structure and parameter values of the optimal control problem (Spence and Starrftt, 1975; Conrad and Clark, 1995). The Hamiltonian of this representative rancher's optimal control problem is non-linear in the control variable. Therefore, an adjustment path to the steady state level of stock of invasive plant species U_t does not follow the most rapid approach path (MRAP). Based on the initial level of infestation, and the parameter values of the model, the adjustment path to U^* may vary. However, I do not intend to conduct such a formal analysis of the time path for this optimal control problem because such an exercise is beyond the scope of this study. Instead of such an analysis, I conduct a graphical analysis of the time path of control and state variables using their initial and steady state values. Figures 5 and 6 show the possible time paths for the steady state variable under the different assumption on the initial level of infestation.

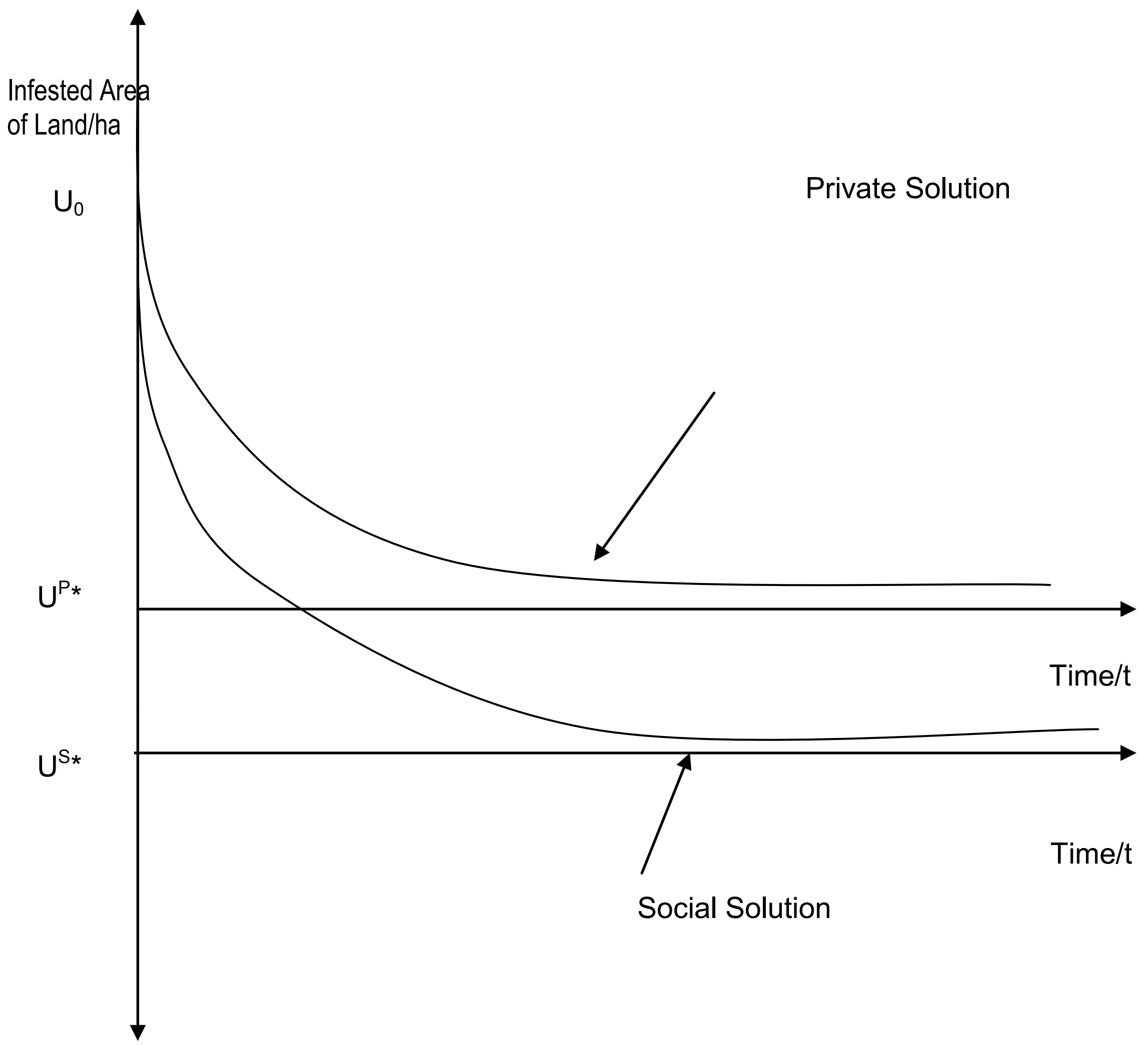
Figure 5. Optimal Time Path of State Variable When U_0<U*



Note: Figure 5 shows the optimal time path of U_t when $U_0<U_s*$ and $U_0<U_p*$. The vertical axis shows the infested area of land in hectares, and the horizontal axis shows the time. According to this figure, the privately optimal time path lies above the socially optimal time path.

If the initial level of infestation U_0 equals the U^{p*} *and* U^{s*}, then $U_t=U^{p*}=U^{s*}$ *and* the time path is a horizontal line with no adjustment. If $U_0<U^p*$ and $U_t<U^s*$ then U_t approaches U^p* and U^{s*} from below as $t \to \infty$ (see Figure 5). In this case, I assume that the initial level of $U_0>0$, and the steady state values for the private U^{p*} and social U^{s*}.

Figure 6. Optimal Time Path of State Variable When U_0>U*



Note: Figure 6 shows the optimal time path of state variable U_t. when $U_0>U_p^*$, and $U_0>U_s^*$. The vertical axis shows the infested area of land and the horizontal axis shows time. According to this figure, the privately optimal time path lies above the socially optimal time path.

If $U_0>0$, and $U_t>U^{p*}$, then U_t approaches U^{p*} from above as $t\rightarrow\infty$. If $U_0>0$, the difference between U_0 and U_t becomes positive. As a result, $U_t>U^{p*}$ and U_t approaches steady state U^{p*} from above as $t\rightarrow\infty$. Similarly, if $U_t>U^{s*}$, then U_t also approaches the steady state value U^{s*} from above, as $t\rightarrow\infty$ (see Figure 6).

Furthermore, to examine the dynamics of allocating labour for controlling hound's tongue, the time path of control variable D_t would look similar to that of U_t in Figures 5 and 6.

According to the time path analysis, when the rancher increases labour to controlling hound's tongue, the infested land area gradually decreases towards the steady state U^{p*} or U^{s*}. Since infested land area decreases over time, an allocation of additional labour for pulling hound's tongue yields diminishing marginal benefits to labour. Therefore, the optimal control policy for the profit-maximising rancher should be a gradual reduction in additional labour for controlling hound's tongue in the rangelands. However, in reality, a control policy for invasive plant species not only depends on labour allocation, but also other biological and social factors, which affect the level of infestation. Policy makers should consider such broader perspectives when they use these findings for formulating invasive plant management policies.

In this analysis, I present both the steady state analysis and the optimal time path analysis for controlling hound's tongue. However, due to the economic and ecological dynamics of the system, a representative rancher has to use a long time horizon to reach the steady state equilibrium. Under such circumstances, the optimal time path analysis may not be useful as a policy tool in controlling invasive plant species in rangelands. Nevertheless, the optimal time path analysis gives several optimal plans related to each time period along the optimal control and state paths. Therefore, such an analysis may provide useful policy approaches to control invasive plant species and thereby improving the overall economic welfare of the wider society. Policy makers should attempt to choose such an optimal control plan for the management of invasive plant species in rangelands. In the next section, I discuss about the first and second best policies related to this optimal control problem.

8. Empirical Analysis

The above analysis provides a theoretical overview of the rancher's optimal management problem. It develops number of relationships that can be used to derive numerical solutions to the optimal control problem. In this section, I estimate numerical values for both private and social steady state equilibria and economic welfare losses to ranchers. To conduct such an empirical analysis, I first provide a description of the study area in the next section using information from field interviews.

8.1. A Brief Profile of the Study Area

I selected the Okanagan valley in BC as a case study. The Okanagan valley is located in the southern interior of BC, and covers more than 20,829 square kilometres. In 2009, the total population of the Okanagan valley was 350,924 accounting for 7% of the total provincial population. The Okanagan valley offers a diverse landscape, rich agricultural land, forest, and mountain peaks. Agriculture, livestock, tourism, retail trade, and manufacturing are the key economic activities in the area. Due to the natural beauty of Okanagan valley, it is also a tourism attraction centre in BC. In recent times, the Okanagan has also become a home to a sizable retired population. After tax, the mean household income in Okanagan Valley is $ 50,301, which is below the average of all of BC (Okanagan Regional District, undated).

8.2. Data and Parameter Sources

I use both ecological and economic data for this study (see Table A.1 in the appendix). Key informant interviews were conducted with eight ranchers and two ecologists in the Okanagan regional district. Semi-structured questionnaires were used to collect the ecological and economic parameters from these key informants. In addition, informal discussions were held with these ranchers and ecologists to understand the general characteristics of ranch operations, controlling behaviour of ranchers and the nature of economic damages from invasive plant species. The economic data relating to the mortality rate of cattle, purchase and selling price of cow calf-units, the price of supplementary feed, the stocking density, and the rental cost of grazing land measured in animal unit months (AUM) were collected through key informant interviews. In addition, a previously prepared farm budget analysis for a 400 cow calf operation was used to obtain parameters related to cow-calf operations in the

Okanagan, BC (Malmberg and Peterson, 2006). Details are provided in Table A.2 to A.4 of the appendix. Ecological data related to hound's tongue such as the date of introduction to BC, current distribution, and ecological carrying capacity were obtained from a GAP analysis report developed by the Ministry of Forests and Range in BC (Miller et al., 2005), and from discussions with other researchers and experts from government agencies. Table 1 provides a description of the basic parameters that are used for this study.

Table 1   Description of Economic and Ecological Parameters

Description	Parameter	Description	Parameter
Intrinsic Rate of Growth	r	Price of Animal Unit Month	p_a
Rangeland Area/ha	L	Person Days	D_t
Infested Land Area/ha	U_t	Wage Rate/$	w
Total Stock of Cattle	X	Price of Replacement Feed/$	p_r
Total Sales	N	Infested Animals	N_i
Price of Cow Calf/$	p_m	Unit Cleaning Cost/$	η
Unit Holding Cost /$	p_h	Replacement Feed	R_t

Note: This table shows the basic economic and ecological parameters of the model that is collected from the key informant interviews and Malmberg and Peterson (2006).

In addition, I needed an estimate of both the private and social damages from the invasion of hound's tongue. The private cost estimate includes forage loss, supplementary feeding cost, and labour cost for treating hound's tongue. There are no studies that measure the economic damage from hound's tongue in Canada or the United States. To carry out an appropriate analysis of economic damages from the invasion of hound's tongue, I use a framework adapted from Hirsch and Leitch (1996), measuring the economic damage from knapweed in Montana. In measuring the social cost of invasion, I adapted the economic damage estimate for knapweed to reflect the damages from hound's tongue. Since both knapweed and hound's tongue are rangeland species and have similar economic and environmental impacts on rangeland productivity, I assume that damages from knapweed are appropriate to represent the cost of hound's tongue.

Key informant interviews revealed that hound's tongue results in recreational damage in the form of reduction in hunting and wildlife watching opportunities as well as soil erosion damages. To measure the recreation expenditure associated with wildlife, I use an approach borrowed from Wallace (1991)[8]. Additionally, I use the approach from Hirsch and Leitch (1996) to measure the social cost from soil erosion due to hound's tongue (see Tables A.4 and A.5 in the appendix). My estimate of the social cost of hound's tongue is $58.34 per hectare, measured as the sum of the costs of recreation loss and soil erosion. I use this value to derive steady state values for the control and state variables and to measure the economic welfare losses to ranchers. In the next section, I discuss the empirical results of the study.

Based on information from Malmberg and Peterson (2006) and the key informant interviews, I define a representative ranching enterprise as one that has the typical ranch size of 400 cows per 3840 hectares. Key informant interviews revealed that ranchers in the Okanagan graze cattle on leased rangelands and purchase supplementary feed from the open market. According to these interviews, ranchers retain adult cows for reproduction and only sell a portion of the initial stock at the end of the grazing season. Ranchers also use both family and hired labour for pulling hound's tongue in the rangeland. Malmberg and Peterson (2006) show that in addition to the labour cost, ranchers spend on trucking, marketing, veterinary care, and winter feed. This brief description represents the general characteristics of ranching operations in BC. I make several assumptions on the representative rancher in the bio-economic model to represent these characteristics of ranch operations in BC. Thus, I would argue that a representative rancher in the bio-economic model reflects a typical picture of ranch operations in BC.

[8] Wallace (1991) use the expression R=(EC)(HW)*S. R represents the change in regional wild life associated expenditure due to infestation. E includes consumptive and non-consumptive wild life associated recreation. C represents the land/use co-efficient. H gives the percentage in wildlife habitat value from infested land. W represents infestation rate and S denotes percentage of expenditure loss to the regional economy.

8.3. **Results**

In this section, I present the results for private and social steady state equilibria for both cases where a representative rancher allocates labour for controlling hound's tongue in his or her rangeland, as well as in the neighbouring public rangeland. This section also shows the net present value (NPV) of producer surplus with and without hound's tongue for both private and social welfare management problems. I also show how private and social welfare losses change when the rancher controls hound's tongue in his or her own rangeland and the neighbouring rangeland.

Private and social steady state solutions for representative ranching enterprise are given in Table 2. The table also presents the NPV of producer surplus for both private and social cases. According to Table 2, at the private U^{p*} and social U^{s*} steady state optimal infestation is 31.61 ha and 14.46 ha respectively. Steady state values for the optimal hound's tongue infestation show that the representative rancher attempts to achieve a low level of infestation because such control creates positive impacts on economic profits through increasing the forage productivity. Although, there is a difference between the private and social steady state values of infestation at such low optimal level, these differences are quite small[9]. Control of hound's tongue creates social benefits such as biodiversity, recreation, and wildlife watching.

[9] I assume a rangeland of 3840 ha. So this difference of 17.15 is less than 1% of the rangeland area.

Table 2. Private and Social Steady State Solutions for a Representative Ranching Enterprise

Variables		**Private Steady State Equilibrium**	**Social Steady State Equilibrium**
	Without hound's tongue	**With hound's tongue**	**With hound's tongue**
Infested Land Area U* (Hectares)	0	31.61	14.46
Labour Allocation D* (Person days)	0	19.56	19.65
Purchase of supplementary feed R*/ton	NA	11.11	5.08
Total forage supply/ton	NA	1350	1350
Number of infested animals N^i	NA	3	1
NPV of annual producer surplus ($)	-32,017.60	-35,464.01	-35,464.46
NPV of annual producer surplus per hectare of infested land/($)1/	NA	-92.35	-92.36
NPV of producer surplus for 10 years, 4% discount rate ($)	-259,691.42	-287,644.88	-287,648.51
NPV of producer surplus for 100 years, 4% discount rate ($)	-784,591.26	-869,045.52	-869,056.47
NPV of welfare loss per hectare of infested land for 10 years, 4% discount rate ($)1/	NA	72.80	72.80
NPV of welfare loss per hectare of infested land for 100 years, 4% discount rate ($)1/	NA	219.93	219.96

Note: 1/ Infested area of rangeland is 384 hectares (10% of total area of rangeland).Total area of rangeland is 3840 hectares.
2/NA=Not available.
3/ Table 2 shows the private and social steady state solutions with and without hound's tongue for the representative rancher. In addition, the table gives the annual NPV of producer surpluses and economic damages for the 10 and 100 years time horizon related to private and social cases.

In addition, there is a small difference between labour allocated for pulling hound's tongue at the private and social steady states. Table 1 shows that at the private steady state, the representative rancher allocates 19.56 person days to control 31.61/ha of infested areas in the rangeland. Similarly, at the social steady state, the representative rancher allocates 19.65 person days to control 14.46/ha of infested areas in the rangeland. This finding indicates that if there are sufficient profits, a private rancher is able to achieve a socially optimal level of control disregarding the difference between the private and social cost of invasion. This is also consistent with the empirical literature on rangeland management under the degradation of ecosystem services. For example, Teague et al., (2009) indicates that ranchers try to maximize profits by maintaining or improving the ecosystem services that produce complementary inputs such as soil fertility and water for their ranching operations. Quaas et al., (2007) shows that under the uncertainty of precipitation, the behaviour of profit-maximizing ranching enterprises leads to environmentally sustainable outcomes related to the management of rangeland ecosystems. Furthermore, Quaas et al., (2007) show that although a risk averse and profit-maximizing rancher does not explicitly take into account the long-term benefits of conserving ecosystem services, the rancher tends to choose a sustainable grazing management strategy, which preserves the long-term sustainability of rangeland. Therefore, my findings are consistent with the current empirical literature on ranching operations and rangeland management.

In Table 2, I use (42) to measure the pre-invasion producer surplus. The net present value of annual pre-invasion producer surplus is $-32,017.60. I use (43) and (44) to measure the net present value of post invasion producer surplus related to the private and social steady state equilibria. The annual net present value of post-invasion producer surplus related to the private case is $-35,464.01. In the private and social cases, the annual net present value of post-invasion producer surpluses are $-35,464.01 and $-35,464.46 respectively. For the 100 year time horizon, the net present value of pre-invasion producer surplus is -$784,591.26. In the private and social cases, the net present value of post-invasion producer surpluses are -$869,045.52 and $-869,056.47 respectively for the same time horizon. Furthermore, the net present value of economic welfare loss per hectare of infested land area is $ 219.93 and 219.96 for private and social cases respectively, for the 100 year time horizon.

These economic welfare estimates show that the NPV of producer surpluses are negative with and without invasion of hound’s tongue. This result indicates that ranching operations in British Columbia generate welfare losses to the individual rancher and society. Therefore, optimal management of invasive plant species may only be able to minimize losses from ranching operations with invasion of hound’s tongue. On the other hand, my welfare estimates focus only on costs and benefits at the steady state. For some cases, it may take a longer time horizon to achieve the steady state equilibrium. Under such a situation, annual net present value of producer surplus may be useful for the formulation of invasive plant management policies.

I also analyze the situation where a representative rancher can allocate labour for controlling hound’s tongue in the neighbouring public rangeland as discussed earlier. To examine the impact of such labour allocation on the steady state equilibrium, I calculate the steady state values for both control and state variables. These steady state values indicate that allocating labour to control hound’s tongue in the neighbouring rangeland creates a considerable difference in the steady state values (see Table 2). For example, at the private steady state, a representative rancher allocates 35.45 person days for controlling hound’s tongue in his or her own rangeland and 17.86 person days for controlling hound’s tongue in the neighbouring rangeland. These values reveal that after a certain stage, a private rancher does not allocate additional labour for controlling hound’s tongue in his or her own rangeland to achieve private benefits, instead switching to allocating labour for pulling hound’s tongue in the neighbouring rangeland. This occurs because declining marginal benefits to labour from controlling hound’s tongue in his or her own rangeland eventually equate with the marginal benefits from controlling hound’s tongue in the neighbouring rangeland even though in the latter case there are no direct grazing area benefits (see Figure 4).

This indicates that a representative rancher may tend to control hound’s tongue in public rangelands because it may increase his or her private profits from ranch operations. Controlling hound’s tongue in public rangelands also generates social benefits such as biodiversity, wildlife watching, and recreation opportunities. However, a private rancher may not be interested in such social gains because these social benefits have public good characteristics and create a free rider problem. Therefore, a private rancher allocates less labour to control hound’s tongue in public rangelands compared to invasive plant control in his or her own rangeland. This situation provides a rationale for the government to intervene in the invasive plant management. This intervention may be implemented by establishing general incentive programs (i.e. payment for ecosystem services or tax relief) for private ranchers. I would argue that such general incentive programs may increase private profits and would lead ranchers to achieve the socially optimal level of control. Under this circumstance, such an indirect government intervention may be more useful to control invasive plant species in rangelands rather than direct government interventions.

Table 3. Steady State Equilibrium when Rancher Controls Hound's Tongue in the Neighbouring Public Rangeland

	Private Equilibrium		**Social Equilibrium**	
	Own Rangeland	**Neighbouring Rangeland**	**Own Rangeland**	**Neighbouring Rangeland**
Person days	35.45	17.86	37.59	18.96
Infested area of land/hectares	62.97	258.52	67.78	303.59

Note: This table gives private and social steady state solutions for the representative rancher when the rancher controls hound's tongue in the representative and the neighbouring rangeland. According to the table, the rancher spends more person days to control hound's tongue in the representative rangeland compared to the neighbouring rangeland

In Table3, I calculate the social steady state equilibrium when the representative rancher allocates labour for controlling hound's tongue in the neighbouring rangeland. According to my calculations, there is no considerable difference between the private and social steady state equilibria (see Table 3). These research findings further confirm that if there are sufficient benefits, private ranchers may tend to control invasive plant species close to the socially optimal level of invasion. However, there is a considerable difference between the social steady state labour allocation for controlling hound's tongue only in his or her own rangeland and the social steady state labour allocation for controlling hound's tongue in both his or her own rangeland and the neighbouring rangeland (see Table 3). In other words, at the social steady state, a rancher allocates more labour to control hound's tongue in his or her own rangeland compared to the situation where he or she can allocate labour to control hound's tongue in both his and her own ranch and the neighbouring public rangeland. Increasing social benefits such as biodiversity, soil fertility, and water tables in the representative rangeland promotes higher private forage productivity. A representative rancher may not be able to gain such benefits from controlling hound's tongue in the neighbouring public rangeland. Thus, the social steady state labour allocation for controlling hound's tongue in the representative rangeland is greater than that of such labour allocation in the public rangeland.

Table 4. Net Present Value of Welfare Losses when Rancher Control Hound's Tongue in Neighbouring Public Rangelands

	Private Equilibrium		**Social Equilibrium**
	Without Hound's tongue	**With Hound's tongue**	**With Hound's tongue**
Annual of producer surplus at 4% discount rate ($)	-259,691.42	-40,261.57	-44,767.09
NPV of welfare loss per hectare of rangeland for 10 years, 4% discount rate ($)	NA	17.41	26.93
NPV of welfare loss per hectare of rangeland for 100 years, 4% discount rate ($)	NA	52.61	81.58
NPV of welfare loss per hectare of infested land for 10 years, 4% discount rate ($)	NA	174.13	269.30
NPV of welfare loss per hectare of infested land for 100 years, 4% discount rate (Can $)	NA	526.09	815.83
Supplementary forage supply at the steady state (ton)	NA	22.14	23.83
Number of infested animals at the steady state	NA	5.58	6.00

Note: This table shows the annual net present values (NPV) of producer surpluses with and without hound's tongue for private and social cases when the rancher controls hound's tongue in the representative and neighbouring rangelands. It also gives NPV of economic damage estimates for the 10 and 100 years time horizon related to private and social cases.

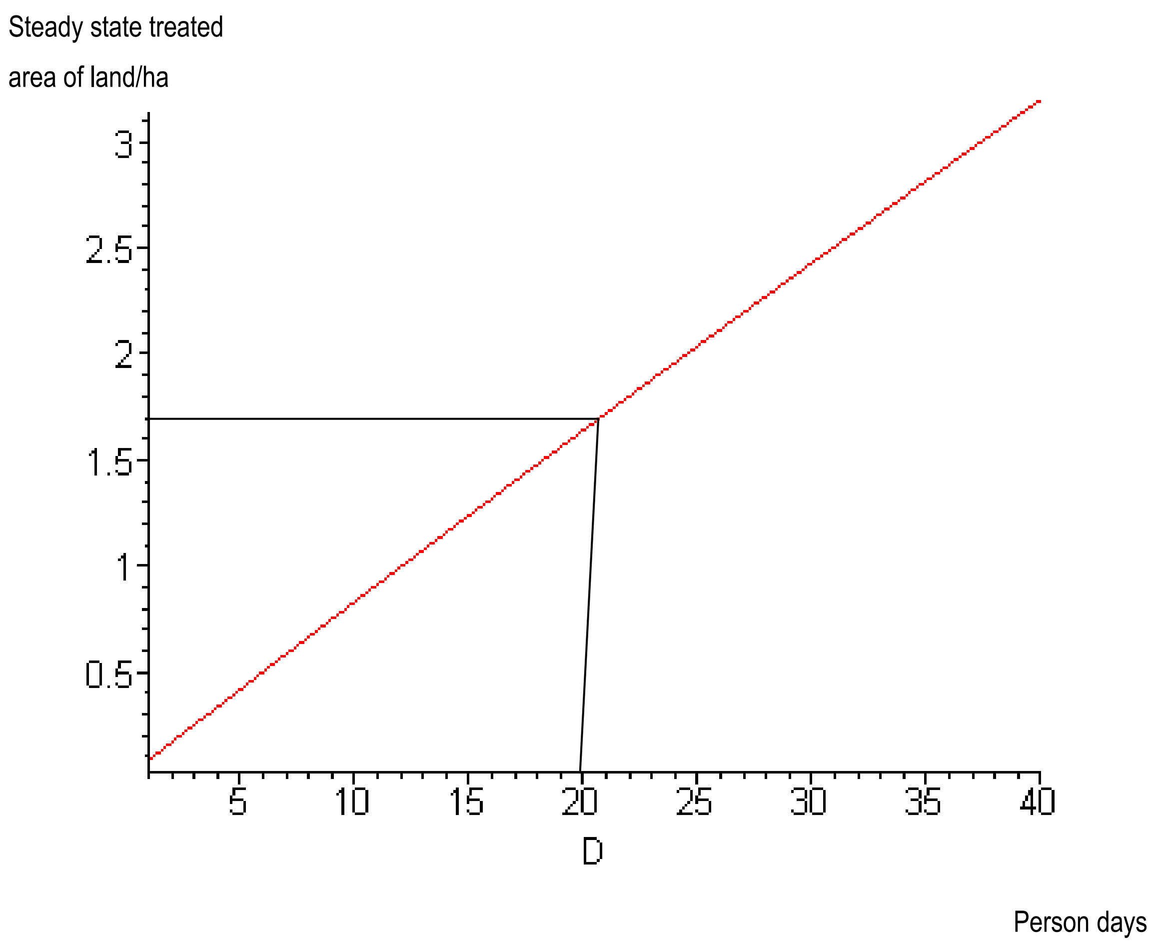
In Table 4, I calculate economic welfare losses for the representative rancher and society when the representative rancher controls hound's tongue in the neighbouring public rangeland. According to this table, the NPV of annual producer surplus is negative at both private and social steady state equilibria. In addition, these negative NPV of annual producer surpluses are larger than the negative NPV of annual producer surpluses related to the situation where the representative rancher only controls hound's tongue in his or her own rangeland. In this bio-economic model, when the rancher controls hound's tongue in the neighbouring public rangeland, he or she has to spend on the additional amount of money for wages. Therefore, the total cost of production in both private and social cases is greater than the total cost of production when the representative rancher spends on controlling hound's tongue only in his or her own rangeland. This causes the considerable difference between the negative NPV values of annual producer surpluses in these two cases.

These negative NPVs also indicate that the optimal management of invasive plant species does not maximise profits but only minimizes economic welfare losses to the representative rancher and the wider society. This finding is similar to the case where the rancher controls hound's tongue only in his/her own rangeland. Therefore, it warrants the implementation of a general incentive program for controlling hound's tongue in the rangelands to maintain good range conditions for improving the forage productivity. Such an improvement in rangeland productivity may lead to minimize economic welfare losses to the wider society.

Table 4 also shows that hound's tongue generates economic damages valued $ 174.13 and $ 269.30 per infested hectare of land for the 10 year time horizon with respect to private and social cases. For the 100 year time horizon, this value becomes $ 526.09 and 815.93 in private and social cases, respectively. These damage estimates indicate that the infestation of hound's tongue creates substantial economic damages to individual ranchers and the wider society. I would argue that the prevention of such damage improves the economic wellbeing of the wider society. Therefore, it is in the public's interest to encourage private ranchers to control invasive plant species via incentive programs.

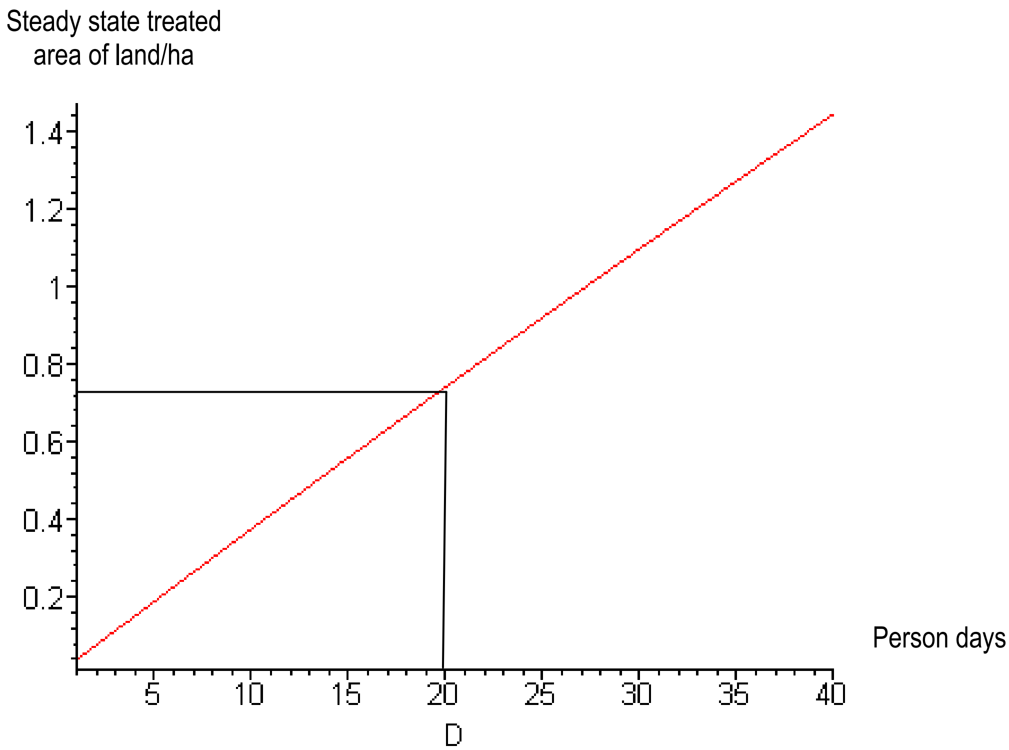
According to the previous analysis, there is a small difference between labour allocation in private and social cases when a rancher controls hound's tongue in the neighbouring rangeland. To clarify the causes of this negligible difference, I plotted the relationship between the number of person days and the steady state treated area of land. A private rancher allocates 20 person days to maintain 1.65/ha of treated area of land (approximately) at the private steady state. However, a private rancher has to allocate same number of person days to maintain 0.7/ha of treated area of land at the social steady state (see Figures 7and 8).

Figure 7. Privately Optimal Area of Infested Land Treated at the Steady State and Associated Control Labour (Person Days)



Note: This figure shows the relationship between privately treated steady state area of land and the quantity of labour allocation to maintain such a steady state. According to this diagram, there is a positive relationship between the steady state treated area of land and the number of person days for controlling hound's tongue. I used the production function TDt=Ut(1-e-βDt) to derive the above relationship. TDt is the privately treated steady area of land in hectares. Ut is the infested area of land in hectares and this is a fixed value. β is the catchebility co-efficient and it lies between 0<β<1. Dt is the number of person days used to maintain the privately steady state control.

Figure 8. Socially Optimal Infested Land Treated at the Steady State and Associated Control Labour Person Days



Note: In Figure 8, the vertical axis shows the socially optimal steady state treated area of land, and the horizontal axis shows the number of person days needed to control hound's tongue in rangelands. The production function in figure 9 is used to derive the relationship between the socially treated area of land and person days. In this case, TDt is the socially treated steady state area of land that represents the output of the production function. Dt is the number of person days, which is the input of the production function. Ut infested area of land, is a fixed factor in the production function.

The production function (treatment function) used to derive the relationship in figures 7 and 8 is concave in D_t at the steady state. The treatment area TD_t is asymptotic to the U_t at the steady state. I use the asymptotic part of the treatment function to illustrate the relationship between the steady state treated area of land and labour allocation in both private and social cases. Therefore, this relationship becomes an upward sloping curve in both cases. I can use this relationship to describe the negligible difference between private and social steady state labour allocations.

As shown in figures 7 and 8, a rancher allocates more labour to maintain socially treated steady state land area compared to the privately treated steady state area of land. At the social steady state, a rancher has to spend more time on searching hound's tongue in the rangeland because he or she has already cleared a substantial portion of his/her rangeland. Thus, a rancher has to bear high marginal cost in controlling hound's tongue at the social steady state compared to the private steady state. However, the marginal benefit of control remains same related to the two equilibrium states. Therefore, a rancher does not substantially increase the amount of labour at the social steady state relative to the private steady state. This causes for the negligible difference between private and social steady state labour allocations in controlling hound's tongue.

8.4. **Discussion and Sensitivity Analysis**

According to these research findings, there is a considerable difference between the treated area of land at the private and social steady states. However, there is no such a difference in the required labour to maintain the treated land area between the private and social cases. The economic intuition behind this finding is that when a rancher considers the social cost of invasion, he or she tends to achieve a nearly complete control over invasive plant species in the rangeland.

My key informant interviews and secondary data reveal that ranching enterprises in the study area currently operate at a low level of profit due to an increase in input prices and losing the export competitiveness in the international market. A reduction in the export competitiveness for beef occurs due to the appreciation of Canadian dollar relative to the US dollar10. Thus, the existing literature on ranch enterprises and information from key informant interviews support the empirical findings of this study. Given these external market dynamics, economic losses result from invading hound's tongue in rangelands may further lower the economic wellbeing of ranching enterprises in BC. Since rangelands provide variety of non-market benefits to society, such deterioration in rangeland ecosystem adversely affects the overall economic wellbeing.

[10] Malmberg and Perterson (2006), shows that the net farm income of representative ranching enterprises in Southern interior, British Columbia per cow calf unit is negative.

This deterioration of both the private and social benefits due to the invasion of hound's tongue provides a strong rationale for providing incentives to ranchers for invasive plant management in rangelands.

These research findings also provide some interesting insight into controlling invasive plant species and achieving social benefits. According to these empirical findings, to achieve the social benefits from controlling invasive plant species ranchers should maintain more control on invasive plant species compared to preserving private benefits. Based on this research finding, I would argue that policy makers and resource management agencies should provide incentives to private ranchers to achieve social benefits and thereby improve economic wellbeing.

From the ecological point of view, controlling hound's tongue creates positive effects on forage supplied by the rangeland. The increase in forage supply reduces the negative effects of cleaning cost [$\acute{\eta} N_t(U/L)$], and increases the producer surplus related to both the private and social steady states. From an economic perspective, a reduction in hound's tongue stock decreases the demand for supplementary feed. This economic adjustment increases the value of $\mu P_R (L-U_t)$ and creates positive effects on the private and social producer surpluses at the steady state. These ecological and economic adjustments provide incentives for an individual rancher to control hound's tongue to a low level of infestation at the steady state. In addition, my field interviews showed that the infested animals not only reduce the economic profit, but also reduce the reputation of the representative rancher as a seller in the market. Therefore, ranchers tend to control hound's tongue to a larger extent and maintain the low level of infestation at the steady state equilibrium.

Despite such a control effort, the representative rancher fails to achieve complete elimination of hound's tongue because it is scattered across the rangeland. My key informant interviews show that the widespread distribution of hound's tongue across the rangeland increases the amount of labour for pulling hound's tongue for a given area of rangeland. The widespread distribution of hound's tongue may create a situation where the marginal cost of achieving complete control (100%) of hound's tongue is greater than the marginal benefits. Due to such ecological and economic dynamics at the steady state equilibrium, the representative rancher would not choose a zero level of hound's tongue infestation. Therefore, the steady state level of invasion remains at a low level but takes a positive value.

My welfare estimates only include social costs such as recreation, wildlife watching, and soil erosion. A neglect of some social cost components may cause negligible difference between private and social welfare losses. However, this analysis reveals that the invasion of hound's tongue creates considerable welfare losses to ranchers and society. This high level of economic welfare losses to society indicates the importance of diverting resources to control hound's tongue for improving economic wellbeing. Therefore, policy makers should take into account this broader social perspective when they use such findings for formulating invasive plant management policies in BC or elsewhere.

To verify the robustness of my results, I carry out a sensitivity analysis on key model parameters (see Table 5). The sensitivity analysis shows that there is a considerable change in the steady state value of infested land area (from 20.96 ha to 6.23 ha) in response to substantially varied values for the unit social cost from baseline value $58.34 (from $25 to $200 per hectare). However, there are no such considerable differences in labour allocation and economic welfare losses to society in response to changes in social cost. Nevertheless, this indicates that changes in social costs are not sufficient to make changes in the socially optimal allocation of labour for controlling hound's tongue. Thus, the inclusion of social costs in the bio-economic model does not alter the private steady state from the social steady state. This is consistent with economic theory when the dynamics of the model favour the corner point solutions for the steady state equilibrium as discussed earlier (Chiang, 1992).

I also used a sensitivity analysis to take into account the uncertainty in ecological and economic parameters of the bio-economic model (see Table 5). An increase in the intrinsic rate of growth may increase both the level of hound's tongue infestation and labour allocation at the steady state and would create economic welfare losses to society.[11] This highlights the uncertainty over key parameter values such as intrinsic rate of growth. It is not possible to find an accurate estimate for the intrinsic rate of growth of hound's tongue in BC or Canada. Thus, I used the best guess estimate obtained from key informant interviews. These sensitivity results indicate the uncertainty of the value of intrinsic rate of growth. Considering these results, I would recommend further research for finding the accurate value for intrinsic rate of growth.

An increase in the price of supplementary feeding material provides incentives for ranchers to increase the removal of hound's tongue in rangelands (see Table 5). I conduct a sensitivity analysis on this parameter value. The sensitivity analysis indicates that the level of hound's tongue infestation decreases, as the price of supplementary feed increases. However, labour allocation for controlling hound's tongue and economic welfare loss do not change considerably due to changes in the cost of supplementary feed. For example, when the price of supplementary feed increases by 100% (from 0.10 to 0.20) the steady state labour allocation increases by only 15% (from 19.66 person days to 19.69 person days). Therefore, this parameter value would not be an important policy variable to alter the steady state equilibrium values of the model.

[11] My sensitivity analysis shows that an increase in intrinsic rate of growth increases both the private and social cost of invasion. However, there is no considerable difference between the private and social losses.

Table 5. Sensitivity Analysis of Key Parameters when the Rancher Controls Hound's Tongue in the Representative Rangeland

Social Cost, c, ($)	Infested Land area, U*, (Hectares)	Labour Demand, D*, (Person days)	NPV of Welfare Loss per Hectare for 100 Years, ($)
25.00	20.96	19.61	189.20
58.34	**14.46**	**19.65**	**219.96**[a]
100.00	10.42	19.67	258.40
200.00	6.23	19.69	350.68
Intrinsic Rate of Growth, r			
0.02	13.98	7.74	143.69
0.05	**14.46**	**19.65**	**219.96**[a]
0.10	15.33	40.35	352.77
0.20	17.46	84.39	643.38
Price of supplementary feed, P_r, (Can $)			
0.049	16.63	19.64	219.96
0.069	**14.46**	**19.65**	**219.96** [a]
0.10	12.02	19.66	219.89
0.20	7.79	19.69	219.86

a Base case.

Note: This table shows the sensitivity analysis of key model parameter values such as social cost, intrinsic rate of growth, and price of supplementary feed on the steady state person days, infested area of land and welfare loss per hectare when the rancher controls hound's tongue in the representative rangeland.

I made several assumptions on functional forms and the structure of the model. A violation of these assumptions may lead to model uncertainty and errors in the model predictions. To measure the economic impacts of hound's tongue, I assume that a representative rancher pays a fixed rent per hectare of rangeland without considering the available AUM. However, in reality, ranchers pay land rent only for the available

AUM in the rangelands of BC. To test the validity of this assumption, I assume that a representative rancher pays only for the available AUM. Thus, I alter the term p_aL in the bio-economic model into $p_a(L-U_t)$. Then, I examine the impact of this change on the steady state equilibrium values. For example, in the private case, the steady state infested land area alters from 31.61/ha to (-1871.91)/ha. Due to the variable rent assumption, the steady state labour allocation changes from 19.56 to 29.72 person days. In the social case, the steady state infested land area changes from 14.46/ha to 27.03/ha under the variable rent assumption. Furthermore, the steady state labour allocation alters from 19.65 to 19.56 person days with variable rent assumption. These results indicate that a change in model assumption make only a considerable difference in the private steady state infested area of land.

As mentioned previously, I extended the analysis to account for the behaviour of the representative ranching enterprise when it is possible to control hound's tongue in the neighbouring rangeland. To verify the robustness of results, I carry out a sensitivity analysis on key economic and ecological parameters for this case, considering uncertainty in the intrinsic rate of growth, impact of neighbouring rangeland on infestation, and prices of supplementary feed (see Table 6).

My sensitivity analysis shows that there are considerable differences in steady state equilibrium values such as infested area of land and labour allocation in response to changes in intrinsic rate of growth (see Table 6). The results in Table 4 indicate that when intrinsic rate of growth changes from 0.05 to 0.10 (by 100%), the steady state labour allocation alters from 35.46 to 58.75 person days (by 65.68%) in his or her own rangeland. In response to the above change in intrinsic rate of growth the steady state infested area of land alters from 62.97/h to 66.84/h (by 6.15%). Thus, the steady state labour allocation in his or her rangeland is more sensitive to a change in intrinsic rate of growth compared to a change in the infested area of land. When intrinsic rate of growth changes by 100% (from 0.05-0.10), the steady state labour allocation increase by 126% (from 17.86 t0 40.40) in the neighbouring rangeland. The steady state infested area of neighbouring rangeland reduces by 39.54% in response to the above change in intrinsic rate of growth. These sensitivity results indicate the uncertainty of the value of intrinsic rate of growth. Considering these results, I would recommend further research to find the accurate value for intrinsic rate of growth.

Table 6. Sensitivity Analysis of Key Parameters When the Rancher Controls Hound's in the Representative and Neighbouring Rangeland

	Own Rangeland		Neighbouring Rangeland	
	D*(Person Days)	**U* (Infested Area of Land/Hectares)**	**E*(Person Days)**	**Y* (Infested Area of Land/Hectares)**
Intrinsic Rate of Growth (r)				
0.02	22.70	55.45	5.45	597.19
0.05	35.46	62.97	17.86	258.52[a]
0.08	49.15	65.22	31.13	180.12
0.10	58.75	66.84	40.40	156.31
Change in impact of neighboring rangeland on infestation (ω and φ)				
0.2	35.46	62.97	17.86	258.52[a]
0.4	28.82	44.25	21.82	105.80
0.7	26.37	29.49	27.24	57.02
0.9	25.78	20.96	31.06	32.61
Price supplementary feed pr, (Can $)				
0.029	17.37	139.61	3.14	-33.12
0.049	35.01	87.67	16.73	361.05
0.069	35.46	62.97	17.86	258.52[a]
0.089	35.71	49.13	18.13	201.35

a Base case.

Note: This table shows the sensitivity analysis of key model parameter values such as social cost, intrinsic rate of growth, dispersal rate, and price of supplementary feed on the steady state person days, infested area of land and welfare loss per hectare when the rancher controls hound's tongue in the representative and the neighbouring public rangeland.

To verify the robustness of steady state results, I carry out a sensitivity analysis of parameters on the impact of neighbouring rangeland on the infestation on own rangeland (parameters ω and φ). When the impact of neighbouring rangeland on the infestation φ increases, both the steady state labour allocation and infested area of rangeland decrease in the representative rangeland (see Table 6). Similarly, there is a decline in infested area in the neighbouring rangeland in response to such change. This sensitivity analysis also shows that an increase in φ lead to an increase in labour allocation for controlling hound's tongue in the neighbouring rangeland. These results indicate that changes in parameters φ and ω make considerable contribution to change in the steady state equilibrium values of labour allocation and infested area of rangelands. I would argue that the results are context specific and may vary depending on these parameter values. Therefore, policy makers should consider such matters in making policy decisions on invasive plant management.

8.5 Limitations

My REM 699 project develops a bio-economic model to measure the economic damages from the invasion of hound's tongue in rangelands in BC. According to the literature review, there are no comprehensive studies, which integrate both ecological and economic aspects to measure economic damages from invasive plant species in BC. This study uses an integrated ecological-economic approach to value the economic impacts of hound's tongue. Therefore, this bio-economic model can be used to measure the economic impacts of rangeland invasive plant species in BC or elsewhere.

In this bio-economic model, I used several assumptions about ranch operations, dispersal of invasive plant species, controlling behaviour of ranchers, and the parameter values. My sensitivity analysis shows that there may be changes in the results of the study, if the parameter values, model structure, and related assumptions are altered. Therefore, policy implications of this study can be applied to controlling rangeland invasive plant species in similar socio-economic contexts where these assumptions are relevant and applicable.

The economic damage estimates of this study only include the forage loss, control cost, soil loss, and loss of recreation. Hound's tongue creates damages to biodiversity and other rangeland ecosystem services. Therefore, my economic damage estimate may under-estimate the true economic impacts of invasive plant species on rangelands.

9. Policy Implications for Invasive Plant Management

I find that direct government interventions may not be useful for controlling or eradicating hound's tongue in rangelands. The findings of this study also indicate that the provision of financial and other types of incentives to ranchers may be useful to achieve the socially optimal level of infestation through controlling invasive plant species in rangelands. In addition, the negative NPV of annual producer surplus reveals that representative ranching enterprise operates at loss. Therefore, optimal management of invasive plant species only leads to minimize economic losses from ranch operations in BC. The absence of profits from ranch operations provides rationale for indirect government interventions for controlling invasive plant species in rangelands. Therefore, I would recommend general incentive programs such as subsidies (i.e. tax relief, payment for ecosystem services, and grants) and income stabilization programs (i.e. government can purchase livestock at a minimum price) for ranching enterprises to control invasive plant species in rangelands. These incentive programs are known as market based policies because they are based on the market. In this section, I elaborate upon the pros and cons of subsidies in invasive plant management, and how such policies affect economic efficiency, social equity, and environmental sustainability.

Provision of a subsidy for ranchers is one market-based policy instrument that can be used to control invasive plant species in rangelands. A subsidy can be provided in the form of grants, loans, or payment for controlling invasive plant species. These subsidies provide incentives to ranchers to take into account the social benefits of controlling invasive plant species in rangelands. Therefore, a provision of a subsidy helps to narrow the gap between the private and social cost of invasion and leads private ranchers towards the socially optimal level of controlling hound's tongue in the rangelands. The advantage of a subsidy is political acceptability and low cost of administering and enforcing subsidies. In addition, it is a flexible policy instrument from an administrative point of view because beneficiaries decide for themselves how to respond to the subsidy in the light of changing circumstances. The disadvantages of subsidies are the difficulty of finding necessary financial resources and the cost of gathering accurate information to determine the correct amount of subsidy on a particular ecosystem service. Since subsidies work indirectly, there may be a time lag in achieving desirable effects on controlling invasive plant species (Stetner, 2003; Howlett and Ramesh, 2003). However, my research findings provide both the private and social damages from invading hound's tongue per hectare of rangeland. Policy makers can use these estimates to determine the value of a subsidy that is given to ranchers for controlling hound's tongue in rangelands. Furthermore, a provision of subsidy to ranchers is consistent with the social equity because it may lead to the redistribution of resources across the wider society. A provision of a subsidy is also able to fulfill the objective of environmental sustainability by providing incentives for ranchers to control invasive plants species. However, this policy strategy lacks the economic efficiency and political feasibility.

Counting on good stewardship could be another policy option. My key informant interviews showed that the BC government does not permit private ranchers to control hound's tongue in adjacent Crown lands. Government thinks that private ranchers may use inappropriate controlling methods that may harm the ecosystem services on Crown lands. As a result, the government directly intervenes to control invasive plant species on public lands in BC. The findings of this study indicate that a private rancher may choose to control invasive plant species to the socially optimal level, if there are sufficient profits generated from such control. In addition, private ranchers are willing to control hound's tongue even in the neighbouring public rangeland because it increases private profits. Under such a situation, the direct government intervention for controlling invasive plant species in BC may not be an economically efficient and socially optimal management strategy. Given that promotion of private stewardship may be a good option for managing invasive plant species in BC rangelands. Ways to support to rancher initiatives to control invasive plants on public lands, subject to adequate environmental controls, should be encouraged.

10. Conclusions and Recommendations

My REM 699 research project analyzes the economic impacts of hound's tongue and measures the economic welfare losses to ranchers and society. Furthermore, it presents policy implications for invasive plant management. Based on the research findings, I present general conclusions of the study and provide recommendations for scientists and policy makers regarding the economic impacts of invasive plant species. In addition, I will identify the areas for future research.

10.1. General Conclusions

Based on the findings of this study, I would argue that direct government interventions into the invasive plant management may yield few incremental social benefits. Therefore, such interventions may not be useful to correct market failures and to improve the efficient allocation of resources in similar situations. This study indicates that the government should offer incentives for private ranchers to achieve an economically efficient and socially optimal level of control of invasive plant species in rangelands. The government can use several policy options such as market-based policy instruments (i.e. payment for ecosystem services) and promoting private stewardship for invasive plant management in BC. Considering the impacts of such policies on economic efficiency, social equity, and environmental sustainability, I would suggest a combination of market and non-market policy instruments for controlling invasive plant species in the rangelands of BC.

Furthermore, the findings of this study indicate that private ranchers behave as the stewards of natural resources, if such behaviour provides sufficient benefits to them. Thus, promoting private stewardship would be a better policy option for invasive plant management in rangelands. These findings are also supported by the current literature of rangeland management. However, the findings of this study are not consistent with direct government interventions to control invasive plant species in similar situations. The sensitivity analysis shows that the steady state equilibrium results are highly sensitive to the changes in the intrinsic rate of growth of invasive plant species. This result indicates the uncertainty of the value of intrinsic rate of growth. Thus, it is necessary to carry out further research to find the accurate intrinsic rate of growth.

It is also noteworthy that my economic damage estimate does not include biodiversity loss and damages to the other ecosystem services by hound's tongue in rangelands. Therefore, the economic welfare loss estimate under-estimates the full social costs from the invasion of hound's tongue. Policy makers need to take this broader social welfare perspective when using my estimates to assist with decision making related to invasive plants in the rangelands of BC or elsewhere. Good economic damage estimates will help prevent invasion and establish recovery programs for ecosystem damages. These welfare estimates may be used to assess the trade offs in resource allocations among various control programs. Hence, the case study of invading hound's tongue in the rangelands of BC can be used to derive theoretically defensible estimates for biological invasion, which can be modeled using an ecological-economic approach.

10.2. Recommendations for Scientists and Policy Makers

This research study attempts to integrate both the economic and ecological aspects of biological invasion in rangelands. As mentioned in the introduction, such integration may help improve both science and policy making related to the invasive plant management (Perrings, et al., 2010). Based on the methodological approach and findings of the study, I present the following recommendations for Ecologists, Economists, and policy makers (Resource Managers/Policy analysts) to follow in valuing the economic damages from invasive plant species.

10.2.1. Economists/Ecologists

Ecologists and economists should understand the importance of integrating the economic and ecological aspects of valuing damages from invasive plant species in rangelands (Dasgupta, et al., 2000). In conducting this research, I communicated with several ecologists in the government and universities to obtain information about the ecological impacts of the invasion of hound's tongue. This communication aided my understanding of the ecological aspects of biological invasion in the rangelands of BC. Based on these discussions, I would suggest that ecologists should help economists to understand the environmental/ecological damages caused by invasive plant species. Following this lead, economists should use the production function approach to quantify such non-market damages from invasive plant species. These two groups of scientists should present the economic valuation results and trade-offs between alternative policy options for invasive plant management to resource managers for making policy decisions. Furthermore, based on such estimates, ecologists and economists should advice resource managers to follow the precautionary approach to avoid the undesirable ecological and economic impacts from biological invasion.

10.2.2. Resource Managers/Policy Analysts

A Pacific Institute for Climate Solutions (PICS) research symposium and Climate Change Impacts Research Consortium (CCIRC) workshops allowed me to discuss policy implications of this research with policy makers in the federal, provincial, and municipal governments. These discussions revealed that policy analysts should have general knowledge about bio-economic modelling, ecology, policy, and management. In short, they should have multidisciplinary backgrounds to understand the work carried out by scientists on valuing economic damages from invasive plant species. Such research projects need a huge amount of financial, human, and physical resources. Resource managers or policy makers should provide those resources and sufficient time for scientists to carry out economic valuation studies about invasive plants species. Furthermore, policy analysts should integrate findings from economic valuation studies into the implementation of invasive plant management policies. I think that such integration would lead to the implementation of economically efficient and environmentally sustainable invasive plant management policies.

10.3. Recommendations for Further Research

This study is a partial equilibrium analysis, and it assumes the impacts of biological invasion on the other sectors of the economy remain constant. However, biological invasion simultaneously affects the different sectors of the economy such as agriculture, livestock, industry, and tourism. Due to the ceteris paribus assumption adapted by economists, a partial equilibrium analysis may fail to capture such economy wide impacts of biological invasion[12]. However, such understanding may be important for formulating regional or national level invasive plant management policies. A general equilibrium analysis may be more appropriate to understand the economy wide impacts of biological invasion and thus, it is a good area for further research.

This analysis shows that there are substantial economic damages to ranchers from biological invasion. However, it does not consider non-market damages such as biodiversity loss, loss of habitat, and damages to other rangeland ecosystem services. A comprehensive environmental cost benefit analysis may be important to provide better policy implications for invasive plant management. Such estimates may be useful to analyze the actual trade off between invasive plant control programs and alternative use of scarce resources. Therefore, a comprehensive economic valuation study is recommended for further research.

In addition, this study has taken the livestock rate as a fixed variable in the bio-economic model. However, many previous studies have used stocking rate as a control variable, and such studies derived policy implications for rangeland management based on the stocking rate (Quaas, 2007; Hein and Weikard, 2008; Finnoff, et al., 2008). The previous studies have also shown that grazing pressure affects the spread of invasive plant species in rangelands (Quaas, et al., 2007; Hein and Weikard, et al., 2008). It is necessary to construct a bio-economic model that includes two control variables (i.e. stocking rate and labour allocation) and two state variables (i.e. growth of hound's tongue and growth of native grass species) for taking into account the complete interactions between the invasion of hound's tongue and ranch behaviour. Accordingly, researchers should focus on such a study for further research.

For mathematical simplicity, this bio-economic model assumes that the biological invasion depends only on the control of parental biomass stock. This model does not consider the various sources of invasion such as transport, international trade, and

[12] Ceteris paribus in economics means that economists assume all other variables or factors except those under consideration are held constant.

climate change. My literature review reveals that such factors make a significant contribution to the biological invasion (Perrings, et al., 2010). Therefore, research studies that analyze the impacts of those factors on the biological invasion and thereby the economic wellbeing of the wider society are recommended for further research.

This study proposes a combination of market and non-market based policy instruments to achieve an economically efficient and socially optimal infestation level. However, this study did not carry out in-depth analysis of those market-based policy instruments and their impacts on the economic welfare of the wider society. Therefore, I suggest that scientists should further study whether market-based policy instruments (i.e. payment for ecosystem services) are adequate to achieve an economically efficient and socially optimal infestation level and thereby improving the overall economic wellbeing of society.

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Appendix. Parameter Tables

Table A.1 Parameters for Empirical Analysis

Variable	Parameter	Value	Source
Intrinsic rate growth of hound's tongue	r	0.05	E-mail communication with Rose De Clerck-Floate, Lethbridge Research Centre, Alberta
Number of cow calf per hectare of land per season (Stock density)	X	400 cows per 3840 hectares	E-mail communication Ann Skinner-Range ecologists in MOFR
Number of hound's tongue infested cow calf	N^i	20 per hundred cow calf	Key informant interview 2011
Annual sales	N	340 calves	Key informant interview 2011
Net selling price of animal	P_m	Can $ 560.50=621+500/1 529.36=560.50-34.14/1	Malmberg, M., and Patterson, T., 2006 See also table A.2 and note 1
Land rental cost per AUM	P_a	Can $ 50 per hectare	e-mail communication Ann Skinner-Range ecologists in MOFR
Hectares of rangeland land required per animal per grazing season	z	9.6/2	e-mail communication Ann Skinner-Range ecologists in MOFR See note 2
Size of representative rangeland area	L	3840/ha	Key informant interview 2011
Hound's tongue infested land area	U_t	10%-20% of the private rangeland	Key informant interview 2011
Unit cleaning cost	ή	Can. $ 13.00 per cow calf/3	Key informant interview, 2011 and See note 3
Unit holding cost	h_c	Can $ 50 per cow calf/4	Malmberg, M., and Patterson, T., 2006 See note 4
Price of replacement feed	P_r	Can. $ 138.00 per ton Can $ 0.069 per pound	Key informant interview 2011

Variable	Parameter	Value	Source
Value reduction of hound's tongue infested cow-calf		10%-15% per pound Can $ 81.93 per animal	Key informant interview, summer 2011 See table A.3
Wage rate	w	Can $ 12.00 per hour	Key informant interview 2011
Interest rate	ρ	0.4	
Feed demand per animal per grazing season	g	6750 pound/5	Key informant interview 2011
Number of person days required for pulling hound's tongue per hectare	D_t	2.5 days (assuming a labourer works 8 hours per day)	Key informant interview 2011
Catchebility co-efficient	β	T_D/D_tU_t=1/1(384) =0.0026	Key informant interview 2011
	μ =g/z=6750/9.6	703.12	

Note: 1/The selling prices of steers and haifer calves are Can $ 621 and 500 respectively. The average price of calves is obtained by (621+500=560.50). To calculate the net market price, I subtracted trucking and marketing cost per cow calf 31.14 from 560.50.

2/According to the key informant interview, 9.6 hectares need to feed cow calf unit per grazing season under the general range conditions. Key informant interview shows that this number varies from 7.2/ h per cow calf units under good range condition to 28.8 per cow calf unit under poor range conditions per grazing season

3/ The rancher has to spend 60-90 minutes for cleaning a cow calf unit at a wage rate is Can.$ 12.00 per hour. Thus the unit cleaning cost per infested cow calf unit is Can. $ 13.00.

4/ Based on data in Malmberg, M., and Patterson, T., 2006, I calculated average veterinary cost and winter feeding cost per cow as Can $ 23 per cow and Can $ 27 respectively. Thus, holding cost per cow is Can $ 50.

5/Cow consumes 25 pounds hay per day. Thus, hay requirements per grazing season is 4500 pounds (25x180). Calf consumes 12.5 pounds per day and thus, feed demand per grazing season is 2250 pounds. Therefore, feed demand of cow calf unit per grazing season is 6750 pounds (4500+2250).

Table A.2 400 Cow-calf Operations/1

Annual sales	Quantity	Price per pound ($)	Sales weight (Pound)	Value per animal ($)	Total value ($)
Cows	72	0.25	1200	300	21600
Replacement Heifers	34	0.83	950	789	26826
Bulls	5	0.28	1800	504	2520
Steer Calves	184	1.07	580	621/2	114264
Heifer Calves	70	1.00	500	500/2	35000
Total	365				200210

Note: 1/Source: British Columbia Ministry of Agriculture and Lands: Planning for profit series 400 cow calf operation-Kamploops-Model Farm Case Study
2/ Sales price of calves =621+500/2=Can $ 560.50

Table A.3 400 Cow-calf Operations and Sales weight

Annual sales	Quantity	Sales weight (Pound)	Total weight of animals (pound)
Cows	72	1200	86400
Replacement Heifers	34	950	32300
Bulls	5	1800	9000
Steer Calves	184	580	106720
Heifer Calves	70	500	35000
Total	365		269420

Notes: Sales weight per animal=269420/365=738.12
Weighted sales price per pound =200210/26942
Market value reduction per pound of beef due to infestation =15%
Reduction of market value per animal due to infestation=(0.74X0.15X738.12)= Can $ 81.93

Table A.4 Invading Hound's Tongue and Value of Recreation Loss

Variables	Value	Adjustment	Notes
E=total consumptive and non-consumptive wild life associated recreation expenditure =217.057 million (1994 USD)	Unit Damage = 217.057 million/ 312800/ha =693.92 (1994 USD)		/1
C=species/land use co-efficient (percentage of wild life supported by rangeland)	0.69		/2
H=Percentage reduction in wildlife habitat value from infested wild land	0.60		/3
W=Percentage of hound's tongue infested area in rangeland	384/3840 =0.10		/4
R=Reduction in wildlife associated expenditure due to hound's infestation per hectare	R=(HWC)xE R=(0.69x0.60x0.10) x693.92 R = 28.72/ha (1994 USD)	FER=1.38 CPI =1.33 1.38x28.72x1.33 =52.71/ha (2011 Can $)	/5

Notes: 1/ According to Hirsch and Leith (1996), total consumptive and non-consumptive wildlife. Associated expenditure E is 217.057 million in 1994 dollars. Total infested land area is 312800 hectares in 1994.

2/ Species/land use co-efficient C shows the relative importance of different land use options in supporting current wildlife populations. Following Hirsch and Leith (1996), we assume that C is 0.69%.

3/ Hirsch and Leitch (1996) assume that monoculture knapweed infestation reduces the 0.08 value of wildlife. According to our informal discussions with ranchers, hound's tongue infestation leads to reduce the value of both domestic and wild life species. In my case, hound's tongue infestation is 10% of total rangeland. Therefore, I assume that hound's tongue infestation reduces a 60% of the value of wild life stock. This includes the cost of wild life damages, diseases, cleaning cost, and deaths of animals.

4/ I calculate the proportion of hound's tongue infested land area W as a 10% (384/3840) of total rangeland based on the information from ranchers in Okanagan.

5/ FER =Foreign exchange rate, CPI=change in price index.

Table A.5 Invading Hound's Tongue and Cost of Soil Erosion

Impacts				Final estimate Can $/ha (2011)	Notes
	Year of Estimate	Unit Damage	Adjustment		
Soil erosion	1994 (USD)	6.13	FER=1.38 CPI=1.33 1.38x1.33x6.13	11.25	1/
			11.25x0.50	5.63	2/

Note: 1/ From Hirsch and Leitch (1996). Based on an average reduction in soil and water conservation benefits of 25% on infested land and an estimate of total benefits of $9.80 per acre in 1993.

2/ According to Hirsch and Leith (1996) knapweed infestation in wild land Montana is 312800 hectares. The hound's tongue infested land area in the private rangeland is 384 acres. Thus, I reduce the Estimated value of soil loss by 50 percent to adjust for the infested area of land.