3 0 R G H O L Q J W K H 5 L V N V D Q G ' D P D J H V I U R

Abstract

Yellow Starthistle (Centaurea Solstitialis) is an annual invasive weed introduced to Western United States from the Mediterranean region. It favours sunny areas and responds aggressively to human disturbances such as road development, firebreaks and animal grazing. It also benefits from longer growing seasons and increased levels of CO2 disproportionately more than native plants. Yellow starthistle (YST) is not yet known to occur in Canada but has been sighted in Washington and northern Idaho. I use a bioeconomic model to produce five study cases of the effects of YST on ranching in BC: (i) a baseline scenario without YST; (ii) a counterfactual scenario where YST is allowed to invade unimpeded; (iii) with the stimulating effects of climate change; (iv) a case where WKH PRGHO LV DXJPHQWHG E\ D KD]DUG IXQFWLRQ WR PLPLF same scenario augmented by climate change. I use an exponential probability distribution for invasion that has been derived from statistical analyses of YST biological characteristics and time to invasion of a representative sample of herbaceous invasives in North America. A representative ranching operation is used as a study site with rangelands being the dominant type of land-use. Producers are assumed to maximise their profit subject to the function of YST spread and the probability of a YST invasion. I found that YST could have significant impacts on ranch operations: severe reductions in yearly profits (-62

9. Conclusions 57

References 59

Appendix 66
I. PCA, Survival and Hazard Analyses.....66
i. Table A.1 ±Survival regression results using PCA scores.....67
ii. Propagule Pressure and Risk of Invasion 68
iii. Survival & Hazard Analyses Results (graphed).....69
II. Table A.2 Parameters for Empirical Analysis.....70
III. Table A.3 Centaurea solstitialis Spread Rates Calculation and Sources.....72
IV. Table A.4 ±BC Cow-Calf Parturition Rate Calculation.....73
V. Table A.5 ±Southern Interior Forage Production.....73
VI. Calculating the a, the a~ and N~ parameters.....74
VII. Sensitivity Analyses Tables 75
Table A.6 ±³1R 6<7´ PRGHO ZLWK YDULDWLRQ LQ FDUU\LQJ FDSD herd growth rate.....75
Table A.7 ±³ <67´ PRGHO ZLWK in the wage rate (control effort), price of beef and YST growth rate. 76
Table A.8 ±³ <67 &&´ PRGHO ZLWK YDULDWLRQ LQ FDUU\LQJ F and price of feed.....77
Table A.9 ±³: 5LVN´ PR15% variation in carrying capacity, price of beef and herd growth rate.....77

List of Tables

Table 1. Glossary of Economic and Biological Parameters 34
Table 2. Optimal Values for Management of a Representative Ranch under Five Scenarios with Assumptions on Climate Change Impacts and Invasion Risk 36
Table 3. Industry-wide results: comparison of five model scenarios 43

List of Figures

Figure 1. Effect of Yellow Starthistle Spread Rate Variation (15% increments) on NPV of Profits: stronger effect of non-linearities on the NPV of profits in the high end of the spread rate values (top 30%). 38

Figure 2. Comparison between model scenarios: variation in key metrics of ranch R S H U D W L R Q D P R Q J I R X U V F H Q D U L R V W K ³ Q R < 6 7 ´ scenario (0%) 42

) L J X U H ³ 1 R < 6 7 ´ 6 F H Q D U L R W K L V I L J X U H V K R Z V F K D Q J H V L Q variation in selected parameters (shown in the legend), starting at the 70% of the value to a maximum of 130%. 45

) L J X U H Scenario: this figure shows changes in results as a function of 15% variation in selected parameters (shown in the legend), starting at the 70% of the value to a maximum of 130%. 45

) L J X U H ³ 5 L V N ´ 6 F H Q D U L R W K L V I L J X U H V K R Z V F K D Q J H V L Q variation in selected parameters (shown in the legend), starting at the 70% of the value to a maximum of 130%. 46

Figure 6 ± 9 D U L D W L R Q R I + H U G * U R Z W K 5 D W H 9 D U L D W L R Q L V J U H D due to a lack of a dampening effect of the hazard of invasion present in W K H ³ 5 L V N ´ V F H Q D U L R 48

Figure 7 - Labour Days and Area Invaded: greater spread rates (100%-130%) of the variation show diminishing returns of effectiveness of search and eradication function. 49

List of Acronyms

AU	Animal Units
AOGCM	Atmosphere ±ocean general circulation models
BAU	Business as Usual
BCCA	% U L W L V K & R O X P E L D Q & D W W O H P H Ç
CC	Climate Change
CFIA	Canadian Food and Inspection Agency
EDDR	Early Detection and Rapid Response
ENGO	Environmental Non-Governmental Organisation
NPV	Net Present value
SFU	Simon Fraser University
YST	Yellow Starthistle

1. Introduction

2.1. IAS in British Columbia

In British Columbia, Frid et al. (2009) examine seven invasive herbaceous species and estimated that in 2008, the range of economic damages was in the order of $1 to $20 million CAD (2006 dollars) for each one of the species.[3] Moreover, by 2020 these damages are projected to increase to between 5 and 60 million dollars per species, with the total mean damages for all seven species projected to be $65 million in 2008, increasing to $139 million by 2020, assuming absence of management. Moreover, the authors point out that these estimates are likely underestimates since economic data were not available for the full range of impacts (Ibid, 2009). Such impacts include biodiversity loss which may be a result of human activity or a result of IAS, what is clear however is that biodiversity loss is positively correlated with invasive species presence (Didham et al., 2005).

2.2. Potential Invasion: Yellow starthistle

A habitat unsuitable for YST in Southern British Columbia is known to exist in Columbian rangelands, which are very well-suited for it climatically and biogeographically. Northern Idaho, for example, is home to 243,000 ha of YST-infested rangeland that expanded from only 10 ha in the 1950s (Ditomaso, Kyser, & Pitcairn, Michael J., 2006). Because of its unpalatability to cows and toxicity to horses[4], YST is a highly noxious agricultural weed. It is responsible for annual damages of $17.1 million USD to cattle production in the state of California (Eagle, Eiswerth, Johnson, Schoenig, & Cornelis van Kooten, 2007). Almost $8 million of the aforementioned sum represents livestock forage losses, while expenditures on YST control amount to $9.45 million per annum. In another study in Idaho, Julia et al. (2007), using an input-output model, found that direct and secondary losses due to YST infestations represent $12.7 million per year, with direct costs estimated to be $8.2 millions and secondary costs of $4.5 million 2005 dollars per year. Furthermore, YST depletes soil moisture reserves; DiTomaso (2005) estimates that on invaded sites, soil moisture

[3] These species include purple loosestrife (Lythrum salicaria), diffuse knapweed (Centaurea diffusa), hawkweed (Hieracium sp.), cheatgrass (Bromus tectorum), Scotch broom (Cystius scoparious), Eurasian watermilfoil (Miriophyllum spicatum) and Dalmatian toadflax (Linaria dalmatica).

[4] YST contains toxins that cause a so-called chewing disease that is deadly for horses

reduction is equivalent to 15%-25% of mean annual precipitation. Water reductions caused by yellow starthistle invasion raise the cost of agriculture and are estimated between $3 million and $15 million annually (Ibid 2005). Water conservation in the Sacramento watershed due to C. solstitialis' alteration of the water regime is estimated to cost from $16 to $75 million dollars per year (Gerlach, 2004).

A range of indirect losses are estimated to result from loss of biodiversity, soil moisture regime changes and losses to tourism that are harder to quantify but are estimated by H[SHUWV WR EH LQ WKH ³WHQV´ (Ditomaso et al., 2006). To make matters worse, interior BC and southern Alberta are in the same ecozone as the current infestations of YST in Washington and Idaho (Montane Cordillera; (Zouhar, 2002)). Given <67¶V HIIHFWLYH SURSDJDWLRQ YLD ZLQG DQLPDO YHFWRUV of climate change, there exists a significant risk of spread and establishment of C. solstitialis in BC (Costello, Mcausland, Costello, & Mcausland, 2003; Ditomaso et al., 2006; Dukes, Chiariello, Loarie, & Field, 2011; Reid, 2006). Lastly, yellow starthistle has become an established invader in the states directly south of %ULWLVK &RORPELD¶V ERU Washington and Idaho, thus presenting an immediate risk of spread into southern BC. As of Summer 2016, VLJKWLQJV RI <67 KDYH EHHQ UHFRUGHG VRXWK R Okanogan County (Scott, L. personal communication).

2.3. Effects of Climate Change on YST

According to Hellmann et al. (2008) and Dukes & Mooney (1999), IAS possess biological characteristics that make them considerably more competitive than native species. However, the range of interactions between native and invasive species subject to climate

was measured as aboveground biomass, stem diameter and height. Interestingly, burning doubled Centaurea establishment suggesting that this plant would perform well in areas that could see an increase in fire frequency because of climate change.

Nitschke & Innes (2008) who modelled fire potential in the Okanagan, a warmer, drier climate will likely result in a 30% increase in fire season length. Furthermore, Toews & Allen's (2009) study of groundwater recharge systems in the Okanagan basin suggests that spring precipitation will probably increase, and summer precipitation will decrease thus leading to drier summers. This is likely to help YST compete with other species since its seed germination and growth trajectories are highly dependent on spring rain events when they grow the fastest while being highly tolerant to dry summers (Ditomaso et al., 2006). As its name suggests, Centaurea solstitialis ³RI VXPPHU VROVWLFH´ KDV survival rates in summers and grows well in arid climates like that of south Okanagan. Its fitness in such climate are, in part, due to its leaf structure, deep taproot and the shape of <67¶V ZLQJHG VWHPV KHOS LW GLVVLSDWH KHDW OLNH D UDGL

2.4. Propagule Pressure, Trade and Risk of Invasion

Successful establishment of sustainable populations of IAS outside their range is positively related to propagule pressure[5], which in its turn depends on the magnitude of human disturbance in a given geographic region. This means that the probability of a species becoming established is increased by the magnitude of the introduction effort (including both the number of individuals released and the frequency of introduction attempts) (Kolar & Lodge, 2001). The pattern des1 2560 Gs88W*n0 145(of)-11 0 0 oes1 21 PF1 11 0 0

costs DULVLQJ IURP $OEHUWD¶V ODUJH FDWWOH LQGXVWU\, even if the potential impact is a fraction of that in BC.

%&¶V IRUDJH DQG JUD]LQJ UHVRXUFHV WRWDO PRUH WKD consists of Crown range (Rothwel, 2005). These resources comprise of forage crops, improved pasture, native range and community pastures. The primary source of feed consists of native grasses and forbs with little or no grain supplementation. About 90% of %ULWLVK &ROXPELD¶V UDQJH-calf and yearling operations for spring, E\ FRZ summer and fall forage where crown range provides ov HU RI FDWWOH¶V WRWDO requirements with the remaining 40% produced on private rangeland and irrigated pasture (Wikeem, McLean, Bawtree, & Quinton, 1993).

Cow-calf operations represent the first step in the production process of beef. Cows are selected for their mothering ability[6], quality of beef and other desirable traits. Mating with select bulls takes place in early summer with the peak of the calving period taking place in spring. On most ranches, the entire production process takes place entirely outside, on open rangelands where cows range and calves nurse. When the calves reach the weight of 500-600 pounds (227-272 kg), they are weaned from their mothers and overwinter outdoors on a forage-based diet (Anonymous, 2006).

Most ranchers in the southern interior manage livestock using altitudinal migration that accesses several vegetation types depending on the season and precipitation. The Bunchgrass, Ponderosa Pine, Interior Douglas-fir and Montane Spruce zones are the key grazing zones in the southern interior region. Due to high variability of topography, terrain, biogeoclimatic zones, soil types, annual precipitation and degree of forest canopy closure, southern interior BC has a wide spectrum of forage yield (Ibid 1993). The geographical focus of the study, the southern interior BC, has an average forage yield of 680 kg/hectare (Wikeem, 1993).[7]

Finally, as it has been described earlier, YST has a predominantly forage-reducing effect, but it is also known to affect other, higher value crops such as vineyards and orchards. Unfortunately the losses from those types of agricultural operations have not yet been quantitatively assessed for those sectors (Ditomaso, Kyser & Pitcairn, 2006). Thus,

[6] 0RWKHULQJ DELOLW\ UHIHUV WR KHLIHUV¶ SURSHQVLW\ WR EH FDUL

[7] Table 4 and Figure 1 in the Appendix show a more detailed forage yield distribution and the derivation of the aforementioned yield value.

2.7. Existing Modelling Research on YST

Despite a wealth of research on established invasive species that attempts to measure

Thus, given the body of knowledge on the impacts of IAS on agriculture, the availability of data on trade in grains and cereals that could contain YST seed, the presence of a ranching industry that would be the most likely target to incur costs from invasion, as well as the similarity of climates between British Columbia and the American states with existing YST infestations, it would be revealing to model the potential evolution of the invasion. Using bioeconomic modelling, a type of modelling that combines biological characteristics of a resource (stock) with the dynamic optimisation techniques commonly used in economics, I can derive the optimal outcomes of a productive system in question. Such a model can then be used to derive insights and answer important questions about a counterfactual reality where, for example, YST is allowed to invade unimpeded, or what management actions can be taken to reduce the risk of invasion.

3. Research Questions

After perusing research on the costs from YST in the U.S., the nature of operations of the cow-calf industry and ecological characteristics of YST and the region of BC where invasion might occur, I constructed a bioeconomic model to answer the following questions:

(1) What are the potential costs of invasion of C. solstitialis on the economic welfare of ranchers in southern interior BC, and what is a privately optimal response to the invader? [8]

(2) What co

4. Methodology

To answer the above research questions, I developed a mathematical model, borrowed from a class of PRGHOV FRPPRQO\ UHFRJQLVHG RSHUDWLRQDO DV WLRQ ¶ PRGH modelling framework, in the context of exploitation of renewable resources, was first developed by Clark, (1976), who specified how dynamic optimisation could be used to answer questions of optimal resource use over time. The main component that distinguishes static from dynamic optimisation models is the presence of a dynamic constraint. This constraint is in the form of a differential equation, which, unlike a static optimisation problem with a constraint exemplified by some linear or non-linear function, outlines a functional relationship between some physical quantities (e.g. quantity of foraged grass) and the rates of change of the resource in question.[9] Dynamic models can be used to answer the question of optimal levels of resource allocation over a defined period of time (Clarke & Reed, 1994; Knowler, 2002). Given this distinction, the structure of dynamic optimisation models is the same as that of static models: an objective function is maximised or minimised subject to a constraint that defines the solution space.

When constructing dynamic optimisation models, the analyst must ensure the logical coherence of the model. In other words, they must select control (variables that I can influence) and state (independent) variables that represent as accurately as possible the multitude of relationships between ecological, economic and logistic systems, among others. Control variables (e.g. cattle offtake[10], or the weed control effort by a rancher), and variables that I cannot control (e.g. beef and feed prices) are combined in an objective function that is then maximised or minimised depending on the objectives of the analyst and the form of the objective function and the constraint. This modelling exercise seeks to maximise the profits of a representative ranch (or industry[11]) by finding optimal levels of control variables (cattle offtake & YST control effort) and associated state variables (herd size, invaded area). Finally, all monetary values used in the analysis are strictly from the

[9] In this case, a differential equation constraint exemplifies the logistic growth of Yellow Starthistle thus showing the change in the rate of growth of the species as a function of time, or the state of

perspective of the representative ranch and as a result do not include indirect costs such as losses to biodiversity and tourism. Thus, the monetary impacts of YST revealed by the PRGHO PD\ EH DQ XQGHUHVWLPDWH VLQFH WKH\ LJQRUH FRVW WKRVH FRVWV VKRXOG EH FRQVLGHUHG WR EH SDUW RI WKH GDPDJH WKDW DUH ERUQ E\ VRFLHW\ DW ODUJH. Such costs could include loss of tourism revenue due to loss of biodiversity and infestation size (Eagle et al., 2007) as well as losses due to changes in the hydrological cycle (Enloe, DiTomaso, Orloff, & Drake, 2004).

The iteration of a bioeconomic model that I developed

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ungrazeable residual that consists of unpalatable native or non-native invasive plants (e.g. K R X Q G ¶ V Wis the number of hectares of forage required per animal per season. Lastly, the g parameter stands for seasonal forage consumption per animal. The last term of the cost expression, $p_r g \frac{R_0}{z}$, represents the total annual expenditure on the forage that has to be bought in the market to replace forage lost through the [illegible] Noy-Meir (1975) estimates that unpalatable residual can reach close to five percent of the rangeland.

It is now possible to formulate the present value of the profit expression which

Following Conrad and Clark (1987), I derived the current value Hamiltonian along with the first order conditions for the above optimal control problem:

Solving this system of equations yields the following steady-state optimal solutions for optimal cattle offtake N* and herd size X*.

$$X^* \quad \frac{1}{2}\frac{a(L \quad R_0)((\quad r)p_m \quad (r \quad G)p \quad p_h}{(p \quad p_m)r} \quad G \qquad (7a)$$

$$N^* \quad \frac{1}{4}\frac{a(L \quad R_0)\,(G \quad r)p_m \quad (r \quad)Gp \quad p_h \quad (\quad r \quad)p_m G \quad (\quad r)Gp \quad p_h}{(p \quad p_m)^2 r} \qquad (7b)$$

A few observations can be made on the above solutions. First, in order for ont1(ol)6(us)113st l(h)30(ts)(or

4.2. :LWK 8QFKHFNHG <67 ,QYDVLRQ ³ <67´

Note that the herd size (X) is bounded by the maximum carrying capacity of the pasture aL. Thus, the sustainability constraint for the pasture can be described by the following expression:

$$X \le \frac{a(L - R_0)}{z} \tag{8}$$

where z is the required number of hectares to feed one cow-calf unit per grazing season[14]. Given that the forage demand for a representative ranch per grazing season per animal is g, the total required forage is gX. With the invader present in this version of the model, some amount of forage (in hectares) will be lost to the YST infestation. The amount of forage available from grazing is therefore:

$$g\left(\frac{L - U - R_0}{z}\right) \tag{9}$$

Where U is the area of the infestation. The remaining forage now has to be met from elsewhere:

$$R \ge g\left(\frac{U - R_0}{z}\right) \tag{10}$$

This problem includes a new dynamic constraint that represents the growth of YST in the form of a logistic growth equation. If no management of the infestation takes place, the propagation of most invasive species can be described using a logistic growth function as

maximisation problem now consists of selecting optimal quantities of offtake ($N^{\#}$) and labour-days ($D^{\#}$) for controlling YST during the grazing season. The extended model consists of the following form of a maximisation problem with two constraints:

max > ( )@

, 0

0

, 0

0

—

Where y represents the intrinsic rate of growth of YST and L is the maximum potential extent of the invasion (can be thought of as U_{max}). T(D) represents the removal effort of YST by a representative rancher and is assumed to have the following functional form:

$$T(D) \quad U(1 \quad e^{\beta D}) \qquad (12)$$

The above equation has the form of a production function that represents control effort in person-days (D) needed to control (diminish) the yellow starthistle infestation, exponentiated by the search parameter, *b* (Widanage, 2012).[15] Moreover, I assume that the output from this effort has an asymptotic limit U

$$X^{\#} \quad \frac{1}{2}\frac{a(L \quad U^{\#} \quad R_0)\,(\quad r)\,p_m \quad (r \quad G)\,p \quad p_n}{(p \quad p_m)\,r} \qquad G \tag{13a}$$

$$N^{\#} \quad \frac{1}{4}\frac{a(L \quad U^{\#} \quad R_0)\,(G \quad r)\,p_m \quad (r \quad)Gp \quad p_n \quad (\quad r \quad)\,pG_m \quad (\quad r)Gp \quad p_n}{(p \quad p_m)^2\,r} \tag{13b}$$

$$U^{\#} \quad \frac{L(e^{\quad bD^{\#}} \quad y \quad 1)}{y} \tag{13c}$$

$$D^{\#} \quad \text{Too long to be analysed, only numerical solutions exist} \tag{13d}$$

Solutions for optimal herd size and off-take with no YST control have the identical form as solutions in the first version of the model except for the addition of the area invaded $\mu U^{\#}$ which dampens the values of both solutions due to its sign. One can also observe that the $U^{\#}$ solution has exponential form and should therefore be sensitive to the values of both *b* and $D^{\#}$. However, $D^{\#}$

Reed, 1994). The risk of invasion is modeled using a survival function to represent the HFRV\VWHP¶V OLNHOLKRRG RI Invaded state in the next time period, t.[17] QRQ

Moreover, I assume that southern BC is subjected to increasing propagule pressure from the U.S. through natural expansion of YST from the relevant border states, as well as trading pressure in potentially contaminated hay and feed from YST-affected states. Given that yellow starthistle has been detected in the states immediately adjacent to the border with British Columbia (EDDMapS, 2017; Scott, L., personal communication), and given that trade in animal feed & seeds is projected to increase according to the Freight Analysis Framework (FAF, 2017) from the five states with active YST invasions (ID, WA, CA, OR, MN) the risk of invasion should increase as well.[18]

Thus, if *Ú*is the moment of ecosystem invasion then the cumulative distribution associated with invasion, denoted F(t), is $F(t) \quad Pr(T \quad t)$. The cumulative survivor function has the following form $S(t) \quad Pr(T \; t) \quad 1 \quad F(t)$. Following Reed & Heras (1992) I use a hazard function as a way of transforming this maximisation problem from a stochastic to deterministic formulation, by introducing a new state variable, y(t), where:

$$y(t) \quad \ln S(t) \tag{15}$$

so that

$$\dot{y}(t) \quad \frac{S(t)}{S(t)} \quad h(t) \tag{16}$$

I assume that the hazard rate, h(t), depends on offtake, N, (and the resulting stocking rate) as well as the biological characteristics of the invasive plant *(b_k)* according to

$$h(t) \quad M \; (N), \; {}_{k}, E \tag{17}$$

and the dynamics of the y variable are given by the following differential equation

$$\dot{y} \quad h(t) \quad M \; (N), \; {}_{k}, E \; ; \quad y(0) \quad 0 \tag{18}$$

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[17] Please refer to the Appendix for a chapter documenting the details of the derivation of the survival function.

[18] %DVHG RQ WKH 8 6 ¶)UHLJKW $QDO\V,Vwith forecasts up to 2045) $) GDWDEDV

Evidence for the relationship between quantity of livestock on rangeland and presence of ungrazeable species is based on research by Milchunas et al. (1989) and Jones (2000) who discovered that there is a positive relationship between the quantity of large ruminants such as cattle and the number of established invasive species.[20] Thus, the probability of YST becoming invasive will depend on the ranch management decision in regard to the stocking rate. Lastly, Pratchett and Gardiner (1991) stress the fact that that maintaining moderate stocking rates is especially important in arid and semiarid regions where recurrent droughts will amplify the effects described above, thus increasing the potential not only for YST to invade at a faster pace but for other, non-palatable alien or native invasives.

Following Clarke & Reed (1994), the expression containing two integrals in equation (14) can be simplified, and after integrating the second term of equation by parts, it can be evaluated in terms of y(t) yielding the following expression:

$$J^{*} \int_{0}^{f} e^{-\delta y(t)} V N, X G N^{\#}, X^{\#}, D^{\#}, U^{\#} a \neg dt \qquad (20)$$

where $N^{\#}$, $X^{\#}$, $D^{\#}$, $U^{\#}$, are based

$$H = e^{-\rho y} V(N, X) - V_0(N^{\#}, X^{\#}, D^{\#}, W^{\#}) - \theta_1 rX\left[1 - \frac{X}{a(L - R\theta)}\right] - N\left[\theta_2 + (M/k)E(\cdot) + D\right] \cdot_{-1} \quad (22)$$

$$\frac{\partial H}{\partial N} = (M/k)E f_N(\cdot) + De^{-\rho y} V(N, X) - V_0(N^{\#}, X^{\#}, D^{\#}, W^{\#})$$

$$e^{-\rho y} V_N(N, X) - \theta_1 - \theta_2(M/k)(E_N(\cdot)) = D \quad (23)$$

$$\frac{\partial H}{\partial X} = G_1 \theta e^{-\rho y} V_X(N, X) + \theta_1 \theta\left[1 - \frac{X}{a(Lw - R\theta)}\right] - \frac{rX}{a(L - R\theta)}\left[\theta_1 - 0\right] \cdot_{-1} \quad (24a)$$

$$\frac{\partial H}{\partial \theta_1} = rX\left[1 - \frac{X}{a(Lw - R\theta)}\right] - N \cdot_{-1} \quad (24b)$$

$$\frac{\partial H}{\partial \theta_2} = (M/k)Ef(\cdot) - D - (M/s_t)fE(\cdot) - D \quad (24c)$$

Given the above FOCs, I can now solve this system and derive optimal levels of N^{**} and X^{**}.

only a 24% increase in aboveground biomass. Still, YST growth responses to CO_2 and nitrate deposition far exceeded those of resident species.[21]

Furthermore, based on the predictions of a number of atmosphere ±ocean general circulation models (AOGCMs), Bradley, Chiariello, Loarie & Field (2009) reason that by

I X W X U H F O L P D W H Z D U P L Q J P D \ H [S D Q G < 6 7 ¶ V U D Q J H E \ Q

Given such variability in results, it is hard to say accurately how much faster YST will expand under conditions of climate change. Especially since growth rate increase is a dynamic process, changing from year to year as environmental conditions vary. Based on observations in the field, Duncan et al. (2004) have cited YST expansion rates of 46% per

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steady-state values as well as net present values (NPVs), their values and sources can be found in Table A.2 in section II of the Appendix.

Table 1. Glossary of Economic and Biological Parameters

Description	Parameter	Description	Parameter
Growth Rate of YST (%)	y	YST infested area (ha)	U
Herd Size (AU)	X	Annual Sales (offtake; AU) ($)	N
Max Stocking Rate (AU/ha)	a	Size of representative ranch (ha)	L
Growth Rate (AU/year)	r	Selling Price of 1 AU	P
Hectares/AU/year	z	Feed Demand per Animal per Sea (kg)	g
Land rental Cost ($)	P_a	Marketing & Trucking ($)	P_m
Cattle Holding Cost ($)	P_h	Replacement Feed (per ton) ($)	P_t
Catchability coefficient		# of Person Days for YST Control (days)	D
Daily Wage Rate ($)	w	Interest Rate (%)	/
YST Hazard Risk		Threshold offtake	$\tilde{N}$

5. Results

In this section I present results from the modelling exercise for a private ranching

in the YST spread rate results in a 59% decrease in profits while the difference between the third and the fourth 15% increment causes a 131% decrease in the NPV_{100} of profits (from $45,406 to -$13,975 ±a decrease greater than 100%). This suggests that at a high end of YST spread rate, i.e. in case of a strong climate change effect, control

spending on control and on replacement feed. This process represents a vicious circle for the rancher which leads to the reductions in stocking rate and profits described earlier. Finally, the effect of higher spread rates is bounded by the search function that dictates the effectiveness of YST control. As I show in the next section, because the search function exhibits diminishing returns, there is a point after which it is not optimal to increase the quantity of labour allocated for control. However, it is important to note that as the technology of weed control evolves, so will the effectiveness of search and eradication of YST. For example, as drone technology becomes more widespread and cheaper it can have considerable effects on the value of steady state solutions through an increase in effectiveness in the search function (Crutsinger, Short, & Sollenberger, 2016). Given the fact that the 0.287 rate of spread is the highest rate I use to represent the effect of climate change, rates as high as 0.46 have been observed in Oregon (Duncan et al., 2004).

5.1.4. Integrating Invasion Risk (+Risk)

Introducing the hazard rate into the bioeconomic model represents a way of internalising risk of invasion into the dynamic profit-optimisation model and exploring how steady-state values change as a result. Following initial mathematical formulation by Reed & Heras (1992) who used the fish stocks to represent a state variable, herd size is the terrestrial equivalent of stock variable. Ranjan, Marshall, & Shortle (2008) for example, adopt a similar approach to Reed & Heras (1992) where fish stock and fishing effort are state and control variables. Unlike Ranjan, Marshall, & Shortle (2008) who formulate the risk of invasion as a function of both stock maintenance and preventative effort (mitigating the impact of IAS arrival), I concentrate only on the influence of invasion hazard via the stock variable (herd size).[24]

As expected, including the hazard rate of YST invasion in a separate model scenario resulted in a slight decrease of both the herd size and the resulting offtake from WKH 3QR<67[25] when compared to the noYST scenario. As shown in section 5.1, the risk of YST invasion reduced offtake and NPV of profits by 19% and 7%, respectively, from the noYST scenario. It should be noted, however, that profitability falls slower than decreases in herd size and

[24] In fact, compared to the formulation in this model, Ranjan, Marshall, & Shortle (2008) added an additional constraint in a form of a function that represents the effects of mitigation efforts aimed at increasing the ecosystem resilience.

[25] A chapter detailing the derivation of the hazard rate of YST invasion can be found in section I. of WKH $SSHQGL[, Survival and Hazard Analyses´

offtake. This is due to the accompanied decreases in costs associated with smaller herd size and offtake, lower overwintering costs, holding costs and marketing costs among others. Overall, this finding can be generalised: at higher levels of herd size, marginal profitability of a ranching enterprise exhibits diminishing returns, a result consistent with diminishing marginal productivity observed in most industries, including ranching (Holechek, et al. 1998).

, W L V L P S R U W D Q W W R Q R W H W K D W W K H Q 3 F R P S D U L V R Q W K H the reductions in NPV_{100} values are quite small. Only a 7% decrease in profits allows for the risk created by YST biological characteristics and historic invasion timelines to be negated. However, the decrease in annual profits between the models mentioned above, is multiplied almost fourfold when climate change is included. As a result, without the effect of climate change, one could make a strong argument that it makes economic sense to take a cut in profits in the current time period in order to ensure a longer-term health (and therefore profitability) of the rangeland. In a scenario where invasion risk is not negated by decreases in stocking rate, then the ranch manager will unknowingly increase the probability of invasion in each consecutive season. This behaviour means that future revenues would collapse sooner. Moreover, another caveat of this finding is that current stocking rates on BC private ranches are already quite conservative. Thus, assuming that there is no effect on YST spread rate from climate change, ranch managers should concentrate on controlling stocking rates in areas where their effect is greatest (more on this in section 8 on Policy and Management Recommendations).

5.1.5. Integrating Invasion Risk & Climate Change (+Risk & CC)

7 K H U H V X O W V F K D Q J H D S S U H F L D E O \ L Q W K H 3 5 L V N & & ´ change- L Q I O X H Q F H G V W H D G \ V W D W H V R O X W L R Q V I U R P W K H 3 < 6 7 within the risk model: offtake decreases by 47% and the NPV_{100} of profits falls by -28%. Integrating the climate effect inflates the value of the residual G(.) function thus resulting in the subtraction of a greater value from the revenue expression leading to an overall reduction of profits.

Moreover, another effect of removing the YST growth and control constraint from the model formulation effectively removes the control variable that influences the spread of YST (days of control effort) thus bounding this model to be solely influenced by one control variable: offtake. The result of this effect is a greater spread between the offtake

YDOXHV ZKHQ FRPSDULQJ ³<67´ DQG ³<67 &&´ VFHQDULRV W
scenarios: 38 AUs and 34.7 AUs vs 39.6 AUs and 24.9 AU respectively. Although ranchers could undertake other preventative efforts such as a more active IAS surveillance regime which would hypothetically decrease the magnitude of the effect of the sole control variable, this method is beyond the scope of this study. Moreover, this result demonstrates that a crude method of risk control that focuses on offtake only may be inadequate thus requiring to be bundled with other prevention methods (see section 7 ± Policy and Management Recommendations).

Another caveat of removing the <67 JURZWK DQG FRQWURO FRQVWUDLQ
VFHQDULRV SHUWDLQV WR KRZ WR SURSHUO\ FRPSDUH WKH UH
WKH <67´ VFHQDULRV %HFDXVH ³<67´ VFHQDULRV H[KLEL
significantly lower NPV_{100}$ SURILWV WKDQ ³5LVN´ VFHQDULRV WKH UHGXFWLRQ LQ SURILWV LV GXH WR
WKH H[WUD FRVWV LQFOXGHG LQ WKH ³<67´ PRGHOV DQ
effectiveness of the search and eradication function. The absence of control effort in the ³5LVN &&´ VFHQDULRV PHDQV WKDW WKH RQO\ OHYHU RI FRQWURO
invasion is through the stocking rate and not mechanical or chemical control of the LQIHVWDWLRQ OLNH LQ ³<67´ VFHQDULRV GHVSLWH D GHFUHDVH LQ RIIWDNH LQ ³5LVN
&&´ VFHQDULRV LV RQO\ WZR WLPHV ODUJHU WKDQ LQ ³<67´ VFHQDULRV
NPV_{100}$ of profits is actually more than threefold higher (232) LQ WKH ³<67 &&´ VFHQDUL
This is because YST control efforts and extra replacement feed (when compared to the ³<67´ DQG ³<67 &&´ VFHQDULRV DUH QRW RSWLPLVHG LQ ³5LVN &&´ VFHQDULR ZKLFK OHDGV WR KLJKHU SURILW YDO
should be made between the ³5LVN´ scenarios and the ³<67´ VFHQDULRV RQ WKH EDVLV RI
revenue and not profits. When one applies this approach, larger differences emerge when comparing revenues: -16% and - ORZHU LQ FDVH RI ³5LVN´ YV ³<67´ D
&&´ YV ³<67 &&´ VFHQDULRV UHVSHFWLYHO\

5.1.6. Model Comparison

A full breakdown of differences between the five model scenarios are summarised in Figure 2 +RUL]RQWDO EDUV UHSUHVHQW 7´ VFHQDULRV) 2UDQJH DQG
assuming that climate change will have no impact on the spread rate of YST, the invasion is expected to result in a 7% reduction in the NPV of profits from the YST-free scenario. $V ,PHQWLRQHG HDUOLHU WKH JUHDWHVW UHGXFWLRQ LQ SU

&&´ VFHQDULRV GXH WR WKH IDFW WKDW WKH SURFHVV IXQ

2010) and apply it to ranchers in BC. Moreover, to lend further support to the assumption that approximately two-thirds of ranchers in BC would be affected by infestation levels IRXQG LQ WKH ³<67´ DQG ³<67 more than &½ of all cattle in BC is reported to be in the regional districts on the edge of the border with Washington and Idaho (BCCA, 2017). Consequently, due to the lack of better data, I assume that 66% of BC ranchers could incur the magnitude of damages computed by the model. Since these results are derived from steady-state values shown earlier for the representative ranch, the same analytical implications apply to the industry-wide data. The benefit of industry data is in showcasing the potential total effect of the YST invasion as exemplified by the magnitudes of direct costs, losses of revenue to ranchers and losses of tax revenue to the government. Given the parsimonious assumptions outlined above, I created

Table 3

6. Sensitivity Analyses

Sensitivity analyses are typically conducted to test the robustness of the model and to explore scenarios where uncertainty of specific parameters is especially high. More specifically, sensitivity analysis involves (1) finding any unexpected relationships between inputs and outputs (searching for errors), (2) finding out whether specific variables have a disproportional effect on the results of the model, and (3) to ensure that variables whose parameters carry a high degree of uncertainty are thoroughly analysed. I selected the following parameters of interest, either due to their structural importance to the model, cyclicality, stochasticity or uncertainty of estimation: the price of cattle (P), the price of replacement feed (P_r), the intrinsic growth rate of YST (y), the growth of the herd (r), the

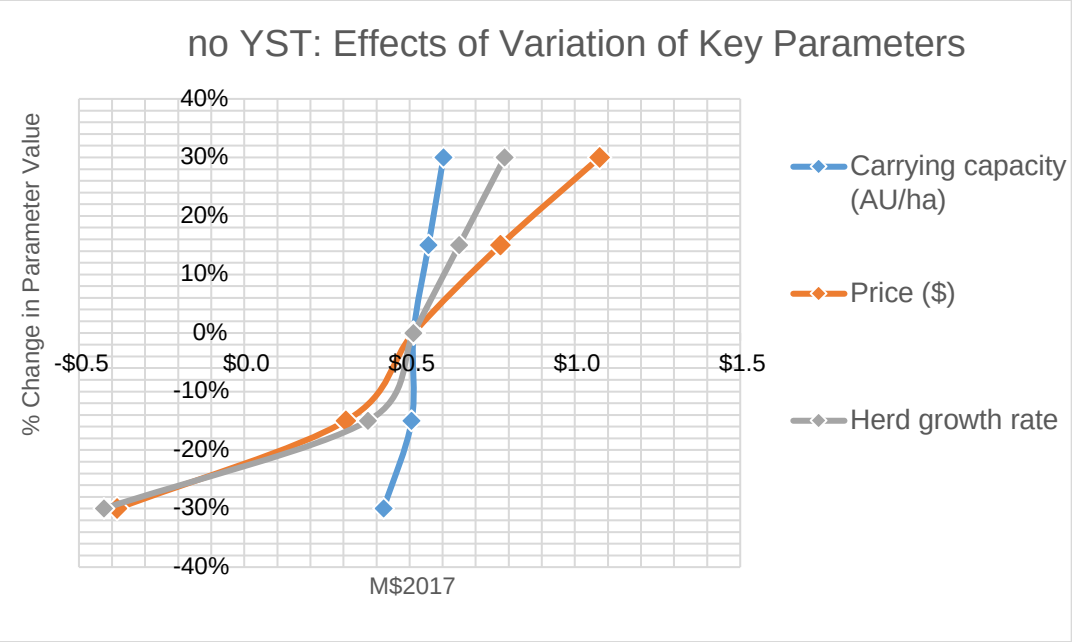

Figure 3. ³1 R < 6 7´ 6 F:thQ figure shows changes in results as a function of 15% variation in selected parameters (shown in the legend), starting at the 70% of the value to a maximum of 130%

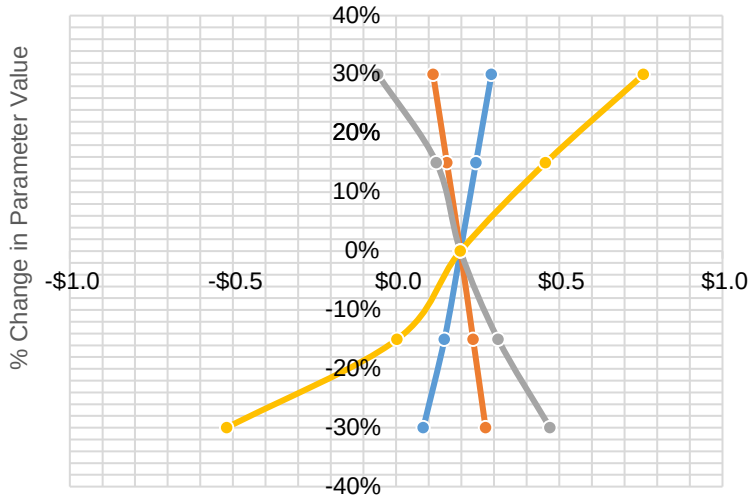

Figure 4. ³+YST ´Scenario: this figure shows changes in results as a function of 15% variation in selected parameters (shown in the legend), starting at the 70% of the value to a maximum of 130%

Figure 5. ³ Risk ´ 6 F H Q ario. This figure shows changes in results as a function of 15% variation in selected parameters (shown in the legend), starting at the 70% of the value to a maximum of 130%

Thus, based on the total range of the values shown by the length of the price line, the maximum selected variation (60%) in the price of beef has the largest effect on the results across all three scenarios. Moreover, non-linearities exist where, for example, a 30% drop in price from the baseline scenario, which is not uncommon in livestock markets, given the cyclical nature of the industry, results in losses of $

climate and consumer preferences. Thus, in the case where YST has established invasive populations, .

TKH WKLUG ODUJHVW HIIHFW RQ WKH SURILWDELOLW\ RI W
HIIHFW RI FKDQJHV LQ WKH SULFH RI VXSSOHPHQWDU\ IHHG
compare WKLV HIIHFW WR RWKHU VFHQDULRV EHFDXVH WKH URO
<67´ DQG ³ 5LVN´ VFHQDULRV LV H[WUHPHO\ VPDOO EHFDXVH
PRGHOV +RZHYHU LQ WKH ³ <67´ VFHQDULR D VZLQJ LQ W
value of the NPV_{100} of profit by $527,843. Furthermore, the price of replacement feed depends on the precipitation and fire regimes in a given year and, as a result, varies greatly from year to year (Wikeem, McLean, Bawtree & Quinton, 1993). Consequently, a 30% price swing is a realistic scenario which can make a fundamental difference in the profitability of a ranching enterprise and its ability to control YST.

Lastly, another variable of interest is the spread of YST under the influence of climate change. Figure 7 demonstrates that there are diminishing returns to labour days spent on search and control of YST. This is due to the functional form of the search function (diminishing returns to search assumption) as well as the value of the search parameter that I found in a study on F R Q W U R O R I K R Q W H Q W L Y H Z H H G LQ WKH Widanage (2012). An important caveat of this observation is that at the higher range of the spread rate, the effectiveness of control decreases and becomes largely ineffective. Assuming no technological growth in the effectiveness of search and eradication and given elevated spread rates, YST-invaded areas may become very difficult to keep in check and likely impossible to reduce according to this scenario.

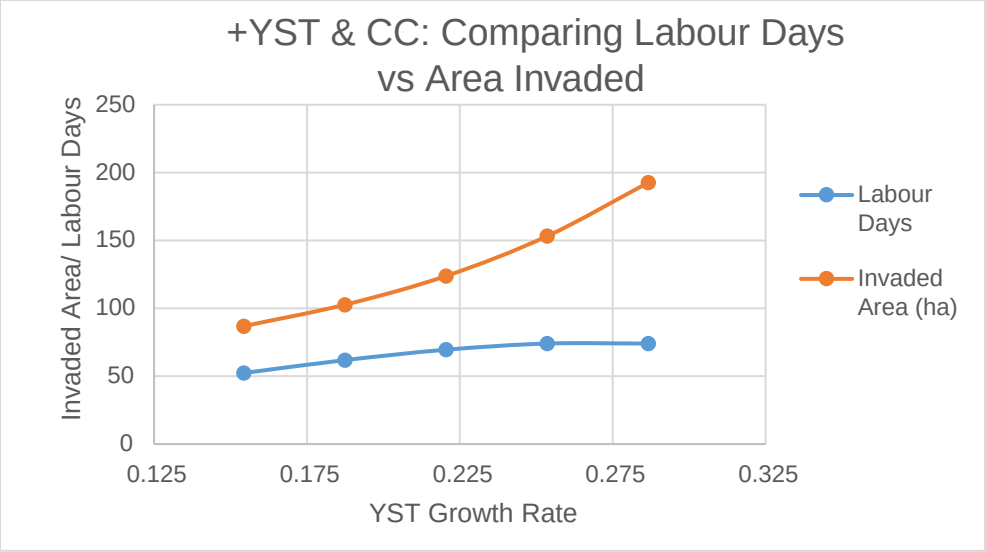

Figure 7. Labour Days and Area Invaded: greater spread rates (100%-130%) of the variation show diminishing returns of effectiveness of search and eradication function

7. Discussion

species like YST once the invasion has occurred. Moreover, Ditomaso, Kyser & Pitcairn (2006) have documented Tm0 Tm0 g0 G[(ha)3(v)11(e)51(do)3(cumen)12(t)-4(ed)] TJETQq0.00[TJET5iDit

by existing research by Epanchin-Niell et al. (2010), the heterogeneity and the state of neighbouring landscapes play an important role during the process of invasion. 8QVXUSULVLQJO\ WKH UDQJH¶V ERUGHU UHJLRQV WHQG WR E from neighbouring farmers, especially when a neighbour is slow at controlling the spread of invasive species or doesn ¶W FRQWURO LW DW DOO GXH WR WKH QDWXU (e.g. beekeeping). Thus, to account for the heterogeneity of the landscape, Holechek, Pieper & Herbel (1998) suggest using salt blocks, additional feed placement and water sources strategically, in order to distribute cattle according to ranchers land management plans. The aforementioned methods may be used to distributed cattle away from areas that are neighbouring landscapes with no natural borders such as ravines or mountains that could prevent the spread of YST. This way, lower-stocked border regions could promote healthier pasture thus serving as barriers against YST invasion.[29]

Another important consideration in maintaining grassland health and diversity,

outlined above, ranches located next to hay distribution centers or other types of feed distributors could find it useful to maintain healthy grassland communities on the boundaries of their rangelands according to the stocking rate specification of this research project in order to maximise their preventative actions.

8. Management Recommendations

Prevention, control or eradication of invasive species is considered a public good because such efforts reduce the negative externalities of YST, among other invasive species. The government of British Columbia has developed an invasive species Early Detection and Rapid Response (EDRR) plan that explicitly acknowledges the acceptance of early response protocols as the most cost-effective method for controlling invasive species (IMISWG, 2014). As its name suggests, the main principle of early detection and rapid response protocols is to detect the species early enough before it establishes populations that are too expensive to be eradicated completely (due to size of infestation), thus presenting only perpetual long-term control as a cost-effective management option (Leung et al., 2002). Long-term control, as previously mentioned, can ramp up extensive costs, especially given the indefinite time horizons of such efforts. However, YST is not on the list of priority invaders that trigger the EDDR protocol (IMISWG, 2016), and as a result has no quantitative risk assessment (for BC or any other Canadian province). In the current instance of EDRR, YST compelled only a brief mention in a form of a reiteration of its economic impacts and other indirect damages in the United States. In contrast, a number of not-for-profit organisations such as Central Kootenay Invasive Species Society (CKISS), Okanagan-Similkameen Invasive Species Society (OASIS), and regional districts like Thompson Nicola (TNRD) have all recognised YST as a Category 1 invader in their respective environments (Thompson-Nicola Regional District, 2015; Wikeem, 2007a). Such a discrepancy in risk assessments exemplifies a problem with the risk assessment component of the provincial EDRR protocol which tends to place a heavier weight on the biological characteristics of an invasive species (Wikeem, 2007b).

Provincial ministries (Forests, Lands, Natural Resource Operations & Rural Development), responsible federal authorities (CFIA) and environmental NGOs (e.g. ISCBC, OASISS) should consider the ranges of costs of invasion outlined in this paper. Governmental authorities outlined above, as well as regional invasive species councils could benefit from organising their invasive species budgets toward targeted, species-specific, preventative actions. For example, preventative actions could entail integrating economic impacts from YST, and other IAS more generally, into the process outlined in the EDRR. At the minimum, making these results accessible to the relevant stakeholders using the infrastructure of governmental platforms would generate a positive externality as a result of greater public awareness and official recognition of the risks of invasive

species such as YST.[30] Furthermore, it is especially important to focus on prevention because given the results outlined in the ³ZLWK LQYDVLRQ´ DQG ³ZLWK FOLP scenarios (³<67´ DQG ³<67´), economically optimal management strategies involve only perpetual control. Perpetual control, in the context of optimal control modelling, means keeping the invasion at 91 ha or 124 ha respectively (in the case of ³<67 &&´ DQG QRW HDGLFDWLRQ), which is highly costly and likely ineffective. As a result, monetary damages outlined in this study should be accounted for by decision makers when evaluating the allocation of funds to EDRR early enough to ensure detection and feasible eradication of YST populations.

When considering the long-term repercussions of allowing YST to invade British &RORPELD¶V 2NDQDJDQ DQG &KDUOHVRQ

management techniques outlined earlier by helping them recover the lost revenue from diminished stocking rates.

However, given the management recommendations outlined above, it is important to consider the limitations of this type of modelling work. It is noteworthy that the notion of a steady-state solution in the context of a dynamic optimisation model implies that it is the best possible outcome over time given the set of parameters of the model, i.e. price of feed, average size of the ranch, YST spread rate, and every other parameter within the model. Moreover, dynamic optimisation models generate solutions via a construct called [illegible]

9. Conclusions

This project aimed to answer two types of questions pertaining to measuring the costs of invasion in a counterfactual reality: (1) where YST was allowed to invade unimpeded, and (2) where YST invasion risk could be controlled through management actions. In both cases, the principal units of analysis were the effect of YST invasion on ranch profits, the magnitude of control costs and the size of invaded area. My estimates indicate that allowing YST to invade could generate up to $858,003,403 of direct costs to the BC ranching industry over a 100-year period and reduce annual profits by 62%, in comparison to the case where the invasion never occurs. YST could be found on as much as 246,888 hectares of private rangeland and improved pasture, representing over 19% of total cattle grazing area. Furthermore, these results are within the range of findings reported in similar studies on yellow starthistle or similar species found in the academic literature, but with a level of specificity and detail that has not yet been explored previously.

A few important management implications emerge from studying the effects of YST in the British Columbia context: (1) the magnitude of damages and perpetual presence of YST (due to cost-ineffectiveness of eradication) stresses the value of prevention and public awareness of the effects of the invasion, and (2) maximising the role of ranchers as stewards of rangelands in generating some level preventative efforts. The results of this study show that it is possible to minimise the risk of YST invasion by controlling the amount of cattle offtake in tandem with lowering the stocking rate. Assuming no effect from climate change, the offtake rate would need to be lowered by an estimated 19%, resulting in a marginally lower annual profit. Given the magnitude of damages mentioned earlier, such a small reduction of profits may appear to be justifiable.

Finally, my sensitivity analysis shows that the results of my modelling are influenced very strongly by fluctuations in beef prices. As a result, decisions regarding the stocking rate are similarly strongly influenced by beef prices, among other factors, albeit to a much lesser degree. Furthermore, from informal conversations with ranchers in the Kootenay region of BC, fluctuating profitability in the ranching industry may present a psychological barrier to consciously lowering the stocking rates below current rates. Given this issue, I recommend controlling the stocking rate by accounting for spatial features of a given rangeland, e.g. keeping stocking rates lower in areas bordering other land-users, especially high-risk ones (e.g. non-agricultural operations). To conclude, ranchers are on the forefront of fighting biological invasions and have to deal with the resulting costs first

hand. It is in their interest to keep their rangelands YST-free, and to do that, the results outlined in this study may be helpful for improving operating procedures

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Thompson-Nicola Regional District. (2015). Facilities Pest Management Plan for

Appendix

I. PCA, Survival and Hazard Analyses

I follow previous analyses by Barbier et al. (2011) and Knowler & Barbier (2005) who adopted a duration model to represent invasion hazard by analysing the effect of biological

species with the characteristics of YST, it faces a risk of 0.8% which is substantially higher than the average risk of 0.5% for herbaceous species. Thus, although the values are small the difference nevertheless represents 60% in heightened potential for invasion when compared to the average hazard of the sample.

ii. Propagule Pressure and Risk of Invasion

Yellow starthistle has been detected in the states immediately adjacent to the border with British Columbia (EDDMapS, 2017), and given that trade in animal feed & seeds is projected to increase according to the Freight Analysis Framework (FAF, 2017) from the five states with active YST invasions (ID, WA, CA, OR, MN), so is the risk of invasion.[35] Thus, I assume that there is growing propagule pressure from infested areas immediately south of the border and an additional risk from imports in cereals and seeds where YST seeds are most likely to be present. The hazard rate computed in the previous section is scaled by the amount of offtake chosen by ranch managers. It is represented by the $f(\breve{U})$ function that scales the risk of a plant being invasive down if $f(\breve{U}) < 1$ and up if $f(\breve{U}) > 1$. For H[DPSOH LI RIIWDNH LV JUHDWHU WKDQ $ the risk of invasion is being diminished, similarly, if the offtake rate less than 55.9 AU/season, the risk of invasion by YST is increased. I assume that a one-third reduction in offtake increases risk threefold in a linear fashion akin to Barbier et al. (2011). Based on the above assumption I formulate a risk scaling function described in section seven.

[35] For more details on the FAF projections on hay, cereal and seed trade volumes to British Columbia, please see figure 2 in the Appendix.

iii. Survival & Hazard Analyses Results (graphed)

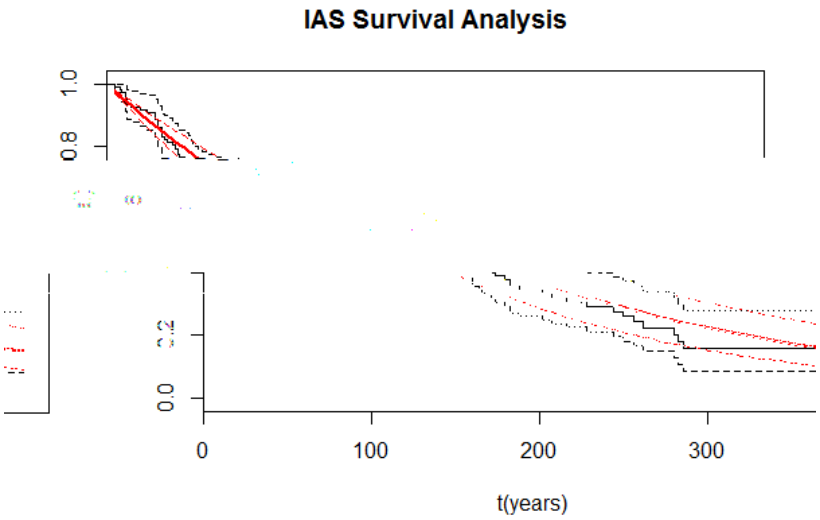

Figure A1 Probability of ecosystem being IAS -free over 300 years

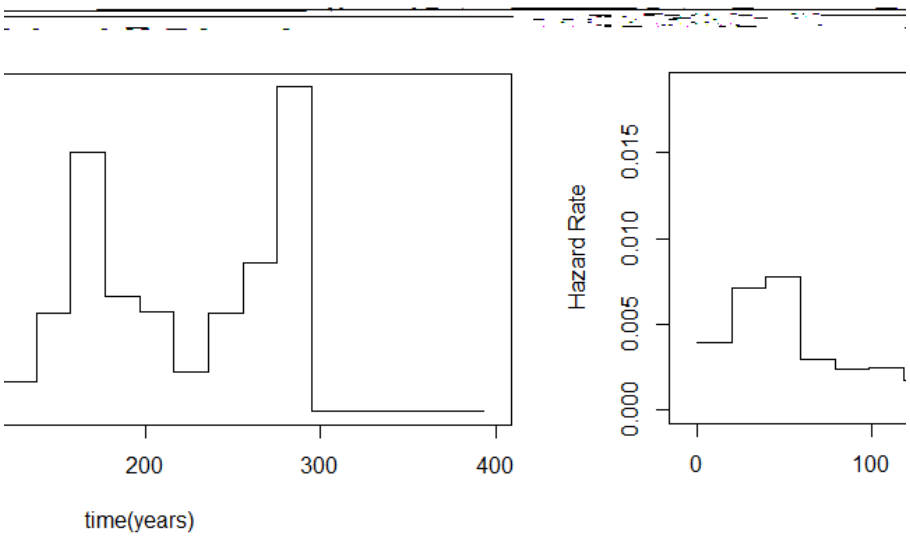

Fig. 6 ±Hazard rate of invasion over 300 year period : increase of hazard rate over 300 year period.

Yellow Starthistle infested land area	U	State Variable #2	N/A
Holding cost	P_h	$65.15 per cow-calf	Rupananda (2012)
Price of replacement feed	P_t	$180 per tonne	Alberta Agriculture a Forestry, (2017)
Wage rate	w	$160/day	Rupananda (2012)
Interest rate	/	0.05	Rupananda (2012)
Feed demand per cow-calf unit per grazing season	g	2324.48 kg	Alberta Agriculture a Forestry, (2017)
Number of person-days required for controlling YST	D	Control Variable #2	N/A

III. Table A.3 Centaurea solstitialis Spread Rates Calculation and Sources

Variable

IV. Table A.4 ±BC Cow-Calf Parturition Rate Calculation

Year	Calves Born (100,000s)	Beginning-of-year inventory	Calving Rate
2006	291.30	540.20	0.54
2007	328.90	519.30	0.63
2008	288.60	514.30	0.56
2009	263.20	494.00	0.53
2010	261.20	447.10	

Table A.8 ±³ <6 7 &&´ PRGHO ZLWK YDULDWLRQ LQ FD
capacity, price of beef and price of feed

+YST&CC					
YST growth rate, y					
77.88	38.39	52.35	86.90	$ 214,159.45	0.16
74.68	36.81	61.86	102.69	$ 160,200.49	0.15
70.47	34.73	69.52	123.84	$ 111,780.20	0.14
64.42	31.76	74.05	153.21	$ 45,405.67	0.13
56.41	27.81	74.05	192.65	-$ 13,974.99	0.11
Price of Beef (P)					
-9.68	-5.58	44.78	166.13	-$519,462.99	-0.02
35.33	18.61	48.42	141.04	$2,450.53	0.07
77.03	37.97	54.83	91.55	$197,099.99	0.16
112.13	52.48	60.31	60.67		

no solution					
31.76	17.22	0.00	0.00	$138,906.54	0.06
77.65	39.55	0.00	0.00	$475,267.78	0.16
106.82	52.18	0.00	0.00	$719,995.78	0.22
124.72	59.33	0.00	0.00	$1,000,657.94	0.25
Herd growth rate, r					
43.91	16.39	0.00	0.00	$126,034.80	0.09
63.85	28.18	0.00	0.00	$319,765.36	0.13
77.65	39.55	0.00	0.00	$475,267.78	0.16
87.77	50.68	0.00	0.00	$661,561.75	0.18
95.52	61.66	0.00	0.00	$867,841.41	0.19