An Investment Analysis Approach to Examining Bio-Control of Invasive Weeds

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Weed scientists, entomologists, ecologists and other scientists have learned a great deal about the biology and bio-control of invasive weeds in North America during the scant three decades that bio-control has been a research priority (Anderson et al., 2003; Asher and Spurrier, 1998; Eisworth and Johnson, 2002; Olson, 1999; Sheley and Petroff, 1999; Shigesada and Kawasaki 1997; Watson. 1985). The population and biology of these weeds in their native habitats in Europe and Asia have been surveyed. A large number of predatory insects and diseases have been identified, collected, screened for safety, and evaluated for introduction. The initial screening is generally completed in the origin country. Biological control agents that have potential are then brought into the country for further evaluation to insure no native species are harmed, and to evaluate the ability of the agent to survive and control the invasive weed. Scientists have also described the substantial environmental advantages of biological controls compared to alternative controls.

Not surprisingly perhaps, given the brevity of the research effort, invasive weeds continue to spread at a fairly rapid pace in the uncultivated private and public lands where they have become established (Asher and Spurrier, 1995). Biological controls, or for that matter other controls, have not been widely adopted by private ranchers or public land managers at rates sufficient to reverse the spread of the invaders. This lag in adoption persists despite considerable public subsidies in the identification and provision of bio-control organisms. The adoption lag persists despite documented declarations by biologists and economists that certain bio-controls are profitable investments (Asher and Spurrier, 1995; Bangsund, Leistritz and Leitch, 1999; Bangsund et al., 2001).

Past research has made good progress on the basic entomology and plant pathology of bio-control agents, but more research is needed to link that to key economic productivity relationships over time. However, both biologists and economists have devoted relatively little research to the dynamics of weeds over multi-year investment horizons. In contrast, economists have developed several bio-economic models for determining profit maximizing annual weed management practices for annual crops (Mortenson and Coble, 1991; King et al., 1993; Kwon et al., 1998). These models typically recommend optimal annual herbicide types and rates in response to annual weed densities, prices, and other variables.

Eisworth and Johnson (2002) recently developed a dynamic optimal control model to determine the optimal "steady state" annual control level for invasive weeds on rangeland. However, the control practice "effectiveness" level was presumed to be constant over time. Annual acreage sprayed with herbicide was the decision variable. Eisworth and Johnson acknowledged that their simple dynamic approach excluded bio-controls for which the biological dynamics differ.

As in Bangsund, Leistritz and Leith (1999), this paper proposes an investment analysis approach for evaluating an initial release and follow-up relocation of agents for a recommended bio-control. The paper focuses on the variable dynamics of control effectiveness level and forage recovery over time. It also recognizes the comparison of alternative site-specific bio-control "investments" is the major economic question of interest to private ranchers and public lands managers. This paper incorporates the heterogeneity of a land manager's land base with respect to weed infestation (free of infestation, infested but with a control, and infested without a control) and bio-control coverage.

Investment analysis of discrete bio-control alternatives is appropriate for the current state of bio-control science. There is a need to efficiently sort specific control options and flesh out the dynamic performance of the options. It may be premature to utilize dynamic optimal control to determine the steady state optimum for the area treated, for example, for a particular treatment whose global acceptability among other alternatives is far from assured. Furthermore, for effective bio-controls, the question is not the optimum annual area treated, as it would be for a herbicide control. The question is what is the best system and whether the system is more profitable than no control. After a successful initial release where the predatory insects are self propagating, there would be limited subsequent annual releases although some insects would be netted and relocated to new sites within the field.

The approach evaluates the private profitability including the stream of future grazing rate changes, the value of any decreases in weed spread, and the effects of bio-control on the terminal value of the manager's land. A total social, as opposed to private, evaluation would also incorporate any economic multiplier effects of increased production and any nonmarket environmental values such as soil, water, air, and wildlife improvements (Bangsund, Leistritz, and Leitch, 1999). The social approach would be appropriate for government policy formulation. Several reasons supported the focus on private profitability in this paper. First, private profitability of a bio-control is more likely to ensure its enduring adoption. Secondly, social benefits could be added later to a control that shows private promise. Thirdly, the private model provides a less cluttered framework for describing key long run dynamics. Finally, the data for private benefits are somewhat more available than those for environmental benefits.

The approach is represented by a discrete discounted present value equation (1). The objective is to maximize net present value (NPV) over the menu of biocontrol practices i = 1, ...,

N. Weed density trends and related variables within the bio-control management unit are specific to the investment i.

$$
\begin{aligned}
\underset{\max_i}{NPV_i} = \sum_{t=0}^{T-1} (1+r)^{-t} \{ & [P_t S_t^i (S_p, F_t^i (W_t^i, R)) - C_t^i (W_t^i, S_t^i, R)] TA_t \\
& + [P_t S_t (S_p, F_t (W^M, R)) - C_t (W^M, S_t, R)] K_t \\
& + [P_t S_p - C_t^f (S_p, R)](L - K_t - TA_t)\} \\
& + (1+r)^{-(T-1)} [V(S_{T-1}^i, Z_{T-1}) TA_{T-1} + V(S_{T-1}, Z_{T-1}) K_{T-1}]
\end{aligned}
\qquad \textbf{(1)}
$$

Subject to:

$$
\begin{aligned}
PIC_t &= bc(t) \\
A_t &= (K_t + TA_t) PIC_t - TA_t \\
TA_{t+1} &= TA_t + A_{t-3} \\
K_{t+1} &= K_t (1 + g(1 - PIC_t)) - A_{t-3}
\end{aligned}
\qquad \textbf{(2)}
$$

where: NPV_i is the net present value for bio-control i in the management unit

$t = 0, \ldots, T-1$ are the years in the planning horizon

r is the discount rate

P_t is the gross return per animal unit in year t

S_t^i is the sustainable stocking rate in year t for bio-control investment i (lack of superscript denotes no control in the model)

S_P is the pre-weed-infestation sustainable stocking rate of the site

F_t^i is the amount of useable grazing forage in the management unit in year t for bio-control practice i

W_t^i is the weed density in year t for bio-control practice i

W^M is the (assumed maximum) weed density in infested areas not (yet) treated

R are management-unit-specific physical and facilities characteristics (such as average precipitation, slopes, soil properties, seed banks for other weeds, fencing, livestock water supplies, etc.)

C^i_t is the production cost per unit area for the management unit in year t for bio-control i

C_t is the production cost per unit area for the management unit in year t for no control

C^f_t is the production cost per ha for the management unit in weed-free areas

TA_t is the total area controlled by bio-control by year t

K_t is the area in the management unit infected by the weed at the time t and not under control

L is total area in the management unit

$V(S^i_{T-1}, Z_{T-1})$ is the change in land value by year T-1 attributable to change in carrying capacity caused by invasive weed density change

Z_{T-1} are changes in factors other than invasive weeds that influence carrying capacity in year T-1

PIC_t is the proportion of land area with invasive weeds that has control, specified as a cumulative density function (CDF) based on expert opinion

A_t is the additional area covered by the bio-control program i in year t (it takes 3 years for a new control to become effective)

g is the proportional annual rate of spread of the weed in the absence of bio-control (modified by the proportion of area with control) bc is a function describing the control area over time

The first term after the summation and discounting operator in (1) represents net returns over time from weed infested areas which are covered by bio-control. The second term describes net returns over time for areas that are infested but have not been treated with the bio-control. The third term describes net returns from uninfected areas. The fourth term is a penalty function and is the present value of the change in land value relative to land free of weeds, and includes the area with bio-control and the area with invasive weeds but with no bio-control. The equations in (2) are the path of weed density with bio-control, the path of the area covered by the bio-control program, and the area with invasive weed infestation. Note the area growth of the invasive is reduced as a result of the bio-control.

W^i_t describes the dynamic effectiveness of the bio-control investment i in reducing the population of the invasive weed over time on an area with the control. This is a key trend in determining the economic viability of the investment. For simplicity, weed populations at period t in (1) are assumed to have uniform spatial density. In practice, this term will vary by the length of time the area has been infested, when the bio-control agent is released, and other site specific factors. Lags in weed density reduction may dampen the effect of expanded area covered by the control. Weed reduction may be slow or weed populations may even aggressively reestablish. Post bio-control weed density trends will vary by bio-control, by invasive weed, and by environment. The durability of the weed density reduction will depend on the inter-generational survivability and locational tenacity of the bio-control in the target environment. Alternative bio-control investments will contain many components such as the number of insects released per unit area, timing of release, mix of insects, size and density of weed patch, sequential releases, and integrated bio-controls with other controls. Identification of recommended and affordable bio-controls constitutes much of the research agenda for bio-control scientists. Once promising control treatments are identified, the long run performance of the controls is crucial to their economic viability.

Figure 1 displays trends in invasive weed canopy cover for three hypothetical control treatments and for No Control. All start from a substantial initial weed density and canopy cover. Without control, the invasive weed continues to become more prevalent and reaches a maximum canopy cover. The hypothetical Decreasing Control treatment (one-time herbicide applications are an example) initially suppresses the weed population but its effectiveness decays over time and weed density tracks toward the maximum. The Static Control treatment initially reduces weed density, but the invasive weed remains at a sustained high density, albeit not increasing. The desired Increasing Control treatment is self perpetuating with increasing effectiveness over time reducing weed canopy cover to a sustained low density.

The data on long run control efficacy are limited, though some medium term information is available. After six to seven years, Kirby et al. (2000) reported the canopy cover of leafy spurge without the control to be about 45% and with control to be about 7%. There was an associated reduction in weed density and an increase in grass yield. An important research priority is to conduct long term follow up effectiveness evaluations of previous bio-control releases on experimental sites and ranches. A large set of data on weed and forage densities associated with the original controls could be used to evaluate control strategies and site specific characteristics that influence control effectiveness.

Another key dynamic relationship, $F^i_t(W^i_t, R)$ in equation (1), is the recovery of useable livestock forage (convertible to sustainable carrying capacity) after the bio-control has been in place for q years. Figure 2 displays three hypothetical livestock forage recovery responses. The vertical axis shows useable forage and note that in general forage utilization in a sustainable system is about 50% of the forage yield. With infestation, forage utilization will decline along the Full Recovery curve with increasing leafy spurge canopy cover (Hein and Miller 1992). At about 40% canopy cover cattle will not graze the forage because it is too closely located to the spurge, which causes blistering of the mouth and other irritations for cattle. The Full Recovery curve assumes that as the weed is controlled useable grass forage and carrying capacity (what ranchers "take to the bank") replace weeds such that rangeland returns to the state prior to weed infestation. In this completely reversible case, forage utilization is restored to its pre weed infestation level when bio-control reduces weeds (Figure 2). However, useable forage and grazing capacity might not be restored to pre infestation levels in some situations even if the bio-control removes all weeds, as shown in the Moderate and Low Recovery curves in Figure 2. For example, the recovery of useable forages might not be reversible due to the disappearance of viable grass seed and crowns after many years of weed infestation. Other weeds or less palatable grasses such as cheat grass (*Bromus tectorum* L.) could occupy the niche vacated by the invasive weed.

If the grass forage has limited potential to recover because of a lengthy history of invasive weeds crowding out the forage, seeding grass seed is an option to re-establish the forage. However, reseeding has been found to be agronomically risky and may not be economically justified (Masters and Nissen, 1998). Climatic conditions following the bio-control might not be conducive to forage recovery. If cattle repelling weeds, for example leafy spurge, remain even at a low level after the bio-control, cattle might be inhibited from eating grass forage that is present. These factors could reduce forage recovery, as illustrated in Figure 2.

Understanding of forage recovery is critical to determining the economic feasibility of bio-control, but relatively little long term work appears to have been done on this issue. If the Low Recovery curve in Figure 2 prevails, this could underlie an economically justified tendency of ranchers and public land managers to “give up” on some of the most established weed patches. It will be useful to understand these relationships over time and space after bio-control. Research on the relationship of total forage response to livestock carrying capacity could benefit by involving animal scientists and range management specialists.

Application and Data

The model is illustrated with control of leafy spurge by flea beetles in southern Alberta. The area controlled by the agent takes the form of an exponential growth function when first introduced. Work on the control of leafy spurge by the flea beetles have indicated after about three years from the initial release of 3,000 beetles, an area of about 1 ha is controlled from one release. Collections can be made after three years from the original release and released at two additional sites, for a total of three sites. This growth pattern and three year interval of collection of beetles at one site to introduce at other sites follows the recommended strategy of successive beetle releases determined effective for control of leafy spurge in the Oldman River Basin (R. Bouchier, personal communication). Based on observations at study sites, it is conservatively estimated that the treated area from any single release will not exceed 1 ha over the 3-year period. For a short time period the function of coverage can be approximated by $3^{(t/3 - 1)}$. This function represents the area in sequential three-year periods which will have been treated by the beetles. Over time though, the rate of area expansion will decline as areas start to overlap and as the beetles consume their food source their rate of reproduction and spread will decline. To account for the increasing and then decreasing rate of expansion of the control area, a tan hyperbolic function is developed that mirrors the initial rate of expansion as indicated above, and then reaches an upper limit after many years of control (Figure 3). The proportion of area controlled is specified as:

$$PIC_t = 0.5 + 0.5 * \tanh(-5.0009 + 4.4912 * \ln(t) - 2.3550 * (\ln(t))^2 + 0.47687 * (\ln(t))^3)$$

where PIC is the proportion of infested area controlled with the bio-control agent and t is the year since the control was initiated. With this equation and one initial release site, it takes about 40 years for control to approach 100% of the infested area.

Changes in control due to relocating some beetles to new sites is specified to occur in three year intervals. The additional area controlled will depend on the infested area and the area that is already under control. This new area of control then becomes part of the total area controlled after three years. The uncontrolled area will continue to grow, but the growth rate is modified over time to reflect that expansion of the invasive weed will not occur in the area already controlled. These dynamic relationships are outlined in equation 2.

The impact of leafy spurge on forage utilization by cattle is small when canopy cover of the spurge is low (<9%), but by about 40% canopy cover cattle will not utilize any of the forage (Hein and Miller, 1992). The Full Recovery curve in Figure 2 indicates an increasing impact on forage utilization with increasing leafy spurge canopy cover. The Moderate and Low Recovery curves were specified such that with no leafy spurge remaining after controls, forage utilization would be 60% and 30%, respectively, of Full Recovery. Full recovery utilizes 50% of forage production. In this analysis, it was assumed that control reduced leafy spurge canopy cover to near zero, or at least to a level that did not impact on forage utilization. Quadratic equation estimates of the three recoveries are in Table 1.

The weed free carrying capacity of the rangeland is important in determining the value of controlling the invasive weed. In southern Alberta, stocking rates on native rangeland in good condition can vary from 0.6 to 3.2 animal unit months per ha, depending on the precipitation area and whether the land is in river bottoms and subject to subirrigation (Wroe et al. 1988). Stocking rates are reduced by about one-half when range condition is poor. Leafy spurge tends to be found in the moist areas, especially along river banks where there can be subirrigation.

The returns from grazing cattle, stocking rate, and rangeland costs will all impact on the NPV of returns from an invasive weed control decision. Parameter values used in the analysis are in Table 2. The return to cow-calf production is the net above the cost of wintering, veterinary, equipment, and costs not related to summer grazing. Prairie grazing is less costly than winter feeding, so returns per animal are higher for the Prairies (eight months of grazing) than moister Parkland and Foothills (six months of grazing). The area costs for the three situations of no invasive weeds, uncontrolled invasive weeds, and bio-controlled invasive weeds includes land area related costs, land taxes and fencing. There is an additional cost for the bio-control situation. Bio-control costs are mostly labor costs associated with scouting and collecting insects to be released at new sites within the field.

The model is applied to a set of differing conditions to estimate the NPV of returns. The time period was 42 years, with a penalty function at year 42 to account for subsequent years. The weed free stocking rate was varied from low (0.75 AUM/ha) to moderate (2.0 AUM/ha) to high

(3.25 AUM/ha). In the Parkland/Foothills, stocking rate should not be at the low end unless the rangeland is in poor condition. In the Prairies, the upper end would be very uncommon. Leafy spurge would seldom be found on arid rangeland with the low rate of stocking density, it would be more likely to be on the higher stocking density rangeland. The initial weed infestation level ranged from no infestation (0%) to 100% infestation. Finally, the recovery of forage in terms of useable forage yield after control was evaluated at three levels, full recovery (50%), moderate recovery (30%) and low recovery (15%). The full recovery would indicate the process is reversible, the low recovery would be indicative of the invasive weed being replaced by plants with lower productivity than the original forage.

RESULTS

The NPV of land with no weeds, 0% initial canopy cover, is the base which to compare the impact of leafy spurge infestation. The NPV for the Parkland/Foothills (Table 3) and the Prairie (Table 4) differ some in magnitude, but the pattern is consistent for the two production regions. With no control of invasive weeds, the NPV of returns becomes negative at about 20 to 40% initial weed canopy cover for the low stocking rate, and at 80% for the high stocking rate. A negative NPV is the result of fixed land costs, such as property taxes and fencing, that need to be covered regardless of the stocking density of the land. The NPV is lowest for no control of invasive weeds, regardless of the weed free stocking rate and initial weed canopy cover. The benefits of control are higher for higher forage recovery, and for the higher weed free stocking rate.

With no control, stocking rate declines with the increased dispersion of the invasive weed to the point where the few cattle remaining do not cover the fixed costs of the land. It would be expected that producers will abandon grazing at some stage of infestation, most likely at the time when the yearly returns to the land become negative. However, at high initial weed canopy cover and effective bio-control, the initial returns can be negative but become positive after 15-20 years because the control agent has been effective.

The NPV is determined for three levels of forage recovery (full, 60% and 30%) after the bio-control of the leafy spurge. The lower the forage recovery, the lower the NPV of grazing and by implication the benefit of control. Forage recovery is relatively more important in determining the NPV when initial weed canopy cover is high, because more of the total land area is affected by the invasive weed. Less than full recovery of the forage combined with low productive land will seldom result in a positive NPV. The net impact is very similar to not controlling the invasive weed. At higher stocking rates, the benefits of controlling the weed are much higher than for not controlling.

The pattern of annual present value (APV) of returns will differ by the initial conditions, a situation not completely expressed by the total NPV in Tables 3 and 4. Two initial conditions (scenarios) are selected as an example and the APV is determined over time (Figure 4). When there is no control of the invasive weed, the APV declines and drops below zero by year 12 when initial weed cover is 80% and stocking rate is 3.25 AUM, and drops below zero by year 28 when initial weed cover is 60% and stocking rate is 2.0 AUM. For the controls, the APV declines for about the first 14 years, at which time the control starts to turn around forage production and use. The APV for the high weed cover scenario drops slightly below zero in year 14 before recovering. By year 30 there is no increase in APV for the controls because the discount factor dominates any gains from control.

It is important to know the recovery rate of useable forage when the invasive weed is controlled. Figure 5 illustrates the annual present value of returns when there is no control and when there is control with forage recovery rate of full, 60% and 30%. In all control cases, there is little difference in returns for the first 10 years. The present value of returns continues to decline over time with no control. The present value of returns for the 30% forage recovery is not much higher than the no control, at most $1/ha/yr. In contrast, the full recovery results in an increase in the present value of returns from year 16 through 26, at which time gains from control are completely exploited and the present value declines because of discounting. The largest annual difference between full recovery and no control is just over $4/ha.

CONCLUSIONS

Past research has made good progress on the basic entomology and plant pathology of bio-control of invasive weeds. Information though is still limited on some of the key dynamic productivity relationships. The recovery of useable forage after controls have been initiated, the time frame of the forage recovery process, and the dynamics of invasive weed and weed density are some of the more critical areas of lacking information. When there is a poor understanding of the linkages to productivity, evaluation of the profitability of proposed bio-controls will require approximations gleaned from limited information about these relationships. The specified relationships might be over stating the response if based on well controlled experiments, or conversely could understate the response. When producers do not observe any major successes or limited adoption by other producers, they are likely to assume the bio-control system is not profitable or profitability is very low. Research on the constraints that are holding back profitability the adoption would facilitate developing a more profitable system producers would adopt.

Agricultural economists can play a useful, but not primary, role in the research agenda. They can help outline the key research relationships linking control to profit, as in the framework above. They can perform bio-economic simulations which illustrate profitability consequences from different hypothesized relationships. These exercises can be used to identify bio-control and weed situations where economic feasibility is and is not attainable. Situations of profitability should be given research priority, and others can be re-evaluated. Once more solid science is available on these key biological relationships, agricultural economists can use modeling to help "fine tune" management recommendations such as determining the size and density of weed patches that are profitable to control, the profitable interval between follow up bio-control releases, and the economic feasibility of combination controls such as bio-controls with reseeding.

The examples and tests used in the application portion of this study illustrates that in general the overall benefits will be small. The magnitude of the benefits depends on the severity of the invasive weed, the productivity of the rangeland in a weed-free state, and the ability of forage production to recover to that in the weed-free state. While the long-term benefits of control are generally positive, returns in the first ten years of the control process are similar to no control. The time to establish the control agent and for the forage to recover results in a fairly significant deferral of benefits from control. Shortening the time frame of control and recovery would increase the net present value of controlling invasive weeds.

References

Anderson, G. L., E. S. Delfosse, N. R. Spencer, C. W. Prosser and R. D. Richard. 2003. Lessons in developing successful invasive weed control programs. *Journal of Range Management* 56: 2-12.

Asher, J. and C. Spurrier. 1998. The spread of invasive weeds in western wildlands. Paper presented at A State of Biological Emergency: The Governor's Idaho Weed Summit. Boise, Ideaho. http://www.blm.gov/weeds/BOISUMMI.WPD.html

Bangsund, D. A., F. L. Leistritz, and J. A. Leitch. 1999. Assessing the economic impacts of biological control of weeds: The case of leafy spurge in the northern Great Plains of the United States. *Journal of Environmental Management* (56):35-43.

Bangsund, D. A., D. J. Nudell, R. S. Sell and F. L. Leistritz. 2001. Economic analysis of using sheep to control leafy spurge. *Journal of Range Management* 54(4): 322-329.

Eisworth, M. E. and W. S. Johnson. 2002. Managing nonindigenous invasive species: Insights from dynamic analysis. *Environmental and Resource Economics* (23):319-342.

Hein, D. G. and S. D. Miller. 1992. Influence of leafy spurge on forage utilization by cattle. *Journal of Range Management* 45(4): 405-407.

King, R. P., D. W. Lybecker, A. Regmi and S. M. Swinton. 1993. Bioeconomic models of crop production systems: design, development, and use. *Review of Agricultural Economics* 15:389-401.

Kirby, D. R., R. B. Carlson, K. D. Krabbenhoft, D. Mundal and M. M. Kirby. 2000. Biological control of leafy spurge with introduced flea beetles (*Aphthona spp.*) *Journal of Range Management* 53(3): 305-308.

Kwon, T. J., D. L. Young, F. L. Young and C. M. Boerboom.1998. "PALWEED:WHEAT II: Revision of a Weed Management Decision Model in Response to Field Testing." *Weed Science*, (46):205-213.

Masters, R. A. and S. J. Nissen. 1998. Revegetating leafy spurge (*Euphorbia esula* L.)-infested grasslands with native tallgrasses. *Weed Technology* 12: 381-390.

Mortensen, D. A. and H. D. Coble. 1991. Two approaches to weed control decision-aid software. *Weed Technology* 5:445-452.

Olson, B. E. 1999. Impacts of noxious weeds on ecologic and economic systems. In R.L. Sheley and J.K. Petroff, eds. *Biology and Management of Noxious Rangeland Weeds*, pp. 4-18. Corvallis, Or: Oregon State University Press.

Sheley, R. L. and J. K. Petroff, eds. 1999. *Biology and Management of Noxious Rangeland Weeds*, pp. 4-18. Corvallis, Or: Oregon State University Press.

Shigesada, N. and K. Kawasaki. 1997. *Biological Invasions: Theory and Practice.* Oxford: Oxford University Press.

Watson, A. K. 1985. Integrated management of leafy spurge. Chapter 9, No. 3, Leafy Spurge, Monograph Series of the Weed Science Society of America, 309 West Clark, Champaign IL.

Wroe, R. A., S. Smoliak, B. W. Adams, W. D. Willms and M. L. Anderson. 1988. *Guide to Range Condition and Stocking Rates for Alberta Grasslands 1988.* Alberta Forestry, Lands and Wildlife, Public Lands. Edmonton, Alberta. 33 pp.

Table 1. Forage Utilization (%) Equation Coefficients

Recovery Rate	Intercept	Canopy Cover	(Canopy Cover)^2
Full	49.5	-0.164	-0.0263
Moderate	29.8	-0.0202	-0.0236
Low	14.6	0.0357	-0.0167

Table 2. Returns and selected costs

Grazing Returns	$/hd/yr
Prairie	141
Parkland/Foothills	87
Grazing Costs	$/ha/yr
No invasive weeds	8
No control of invasive weeds	8
Bio-control of invasive weeds	10
Technical Coefficients	
Discount rate (%)	4
Spread rate of invasive weed (%)	2

Table 3. Net present value ($/ha) of returns to rangeland in the Parkland/Foothills with different forage recovery levels and without control.

Weed Free Stocking Rate (AUM/ha)	Percent initial canopy cover of the leafy spurge					
	0	20	40	60	80	100
	Useable Forage Recovery 100%					
0.75	64	22	-17	-52	-85	-115
2	464	360	263	174	90	13
3.25	865	697	542	399	266	140
	Useable Forage Recovery 60%					
0.75	64	13	-33	-74	-112	-148
2	464	336	220	114	16	-74
3.25	865	670	473	302	145	-1
	Useable Forage Recovery 30%					
0.75	64	7	-45	-91	-133	-172
2	464	319	188	69	-39	-140
3.25	865	632	421	230	55	-107
	No Control of Invasive Weeds					
0.75	64	1	-52	-98	-140	-177
2	464	298	156	33	-77	-177
3.25	865	594	364	164	-15	-177

Table 4. Net present value ($/ha) of returns to rangeland in the Prairies with different forage recovery levels and without control.

Weed Free Stocking Rate (AUM/ha)	Percent initial canopy cover of the leafy spurge					
	0	20	40	60	80	100
	Useable Forage Recovery 100%					
0.75	115	65	20	-23	-62	-99
2	603	476	359	251	151	57
3.25	1090	886	699	525	364	212
	Useable Forage Recovery 60%					
0.75	115	55	0	-50	-96	-138
2	603	448	307	179	61	-49
3.25	1090	841	615	408	217	40
	Useable Forage Recovery 30%					
0.75	115	47	-14	-70	-121	-168
2	603	426	268	124	-7	-129
3.25	1090	807	557	320	107	-89
	No Control of Invasive Weeds					
0.75	115	39	-25	-81	-132	-177
2	603	400	228	78	-56	-177
3.25	1090	760	481	237	20	-177

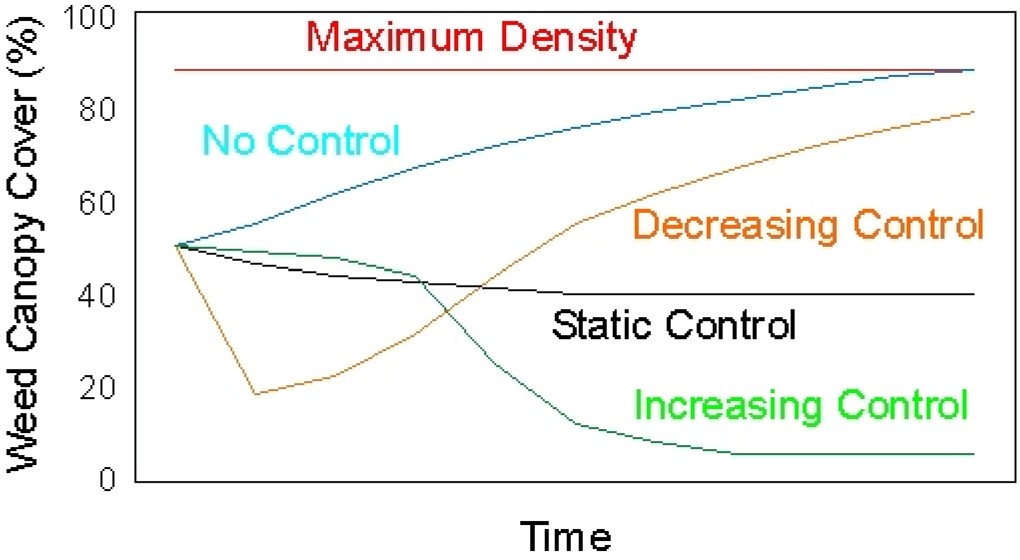

Figure 1. Hypothetical invasive weed density trends over time following a recommended bio-control

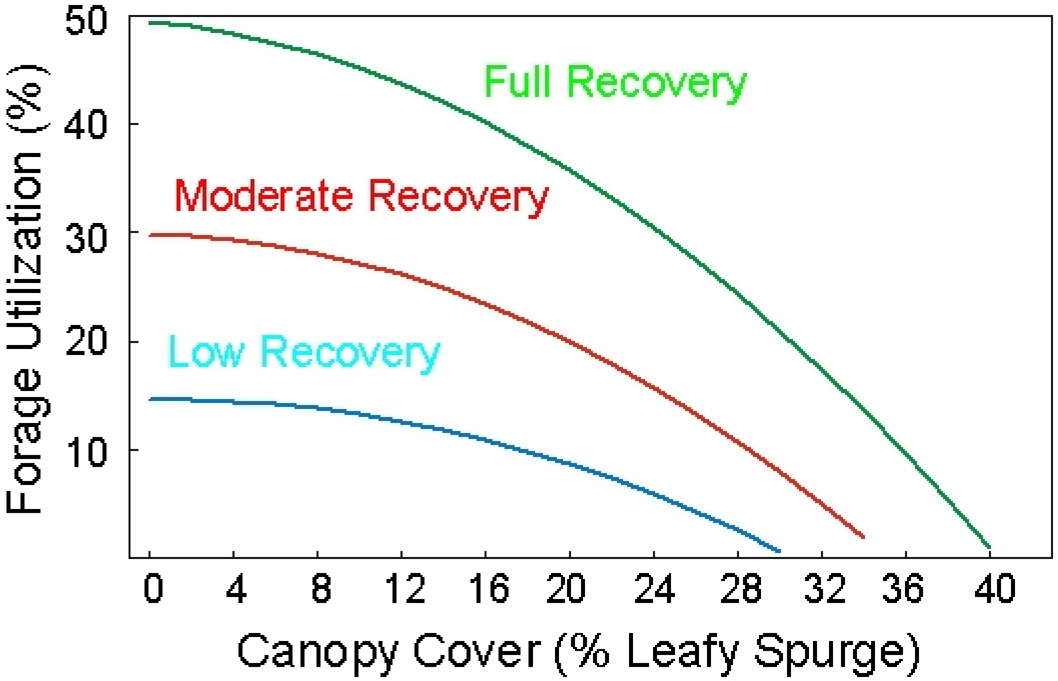

Figure 2. Useable forage recovery in year q following bio-control as a function of surviving invasive weed canopy cover after q years.

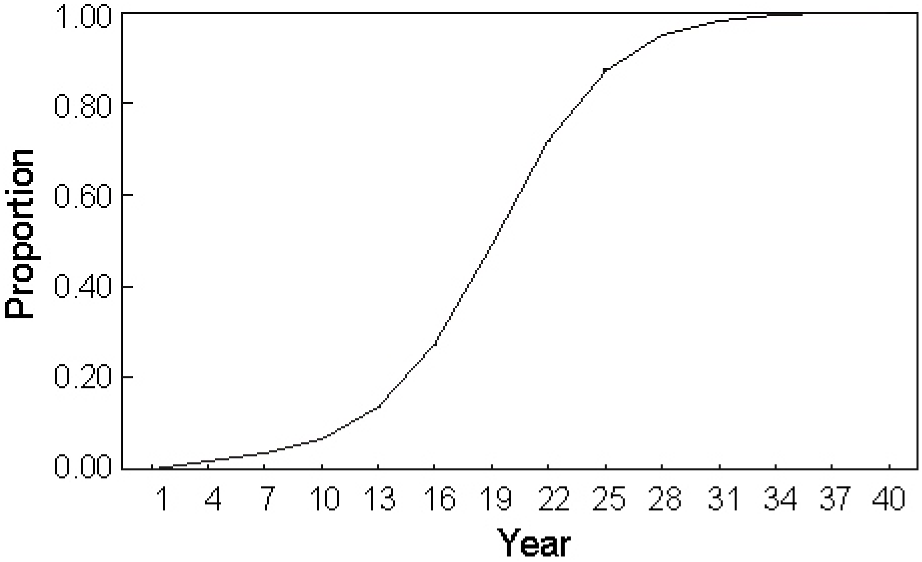

Figure 3. Proportion of area controlled by the bio-control agent over time.

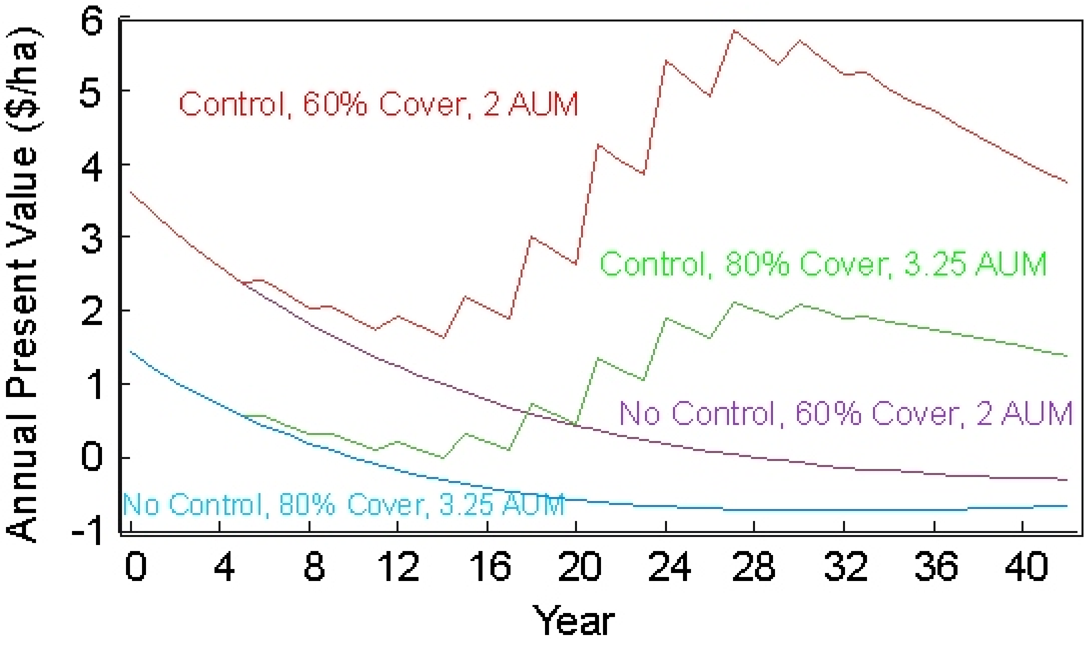

Figure 4. Annual present value for two scenarios, with control and with no control.

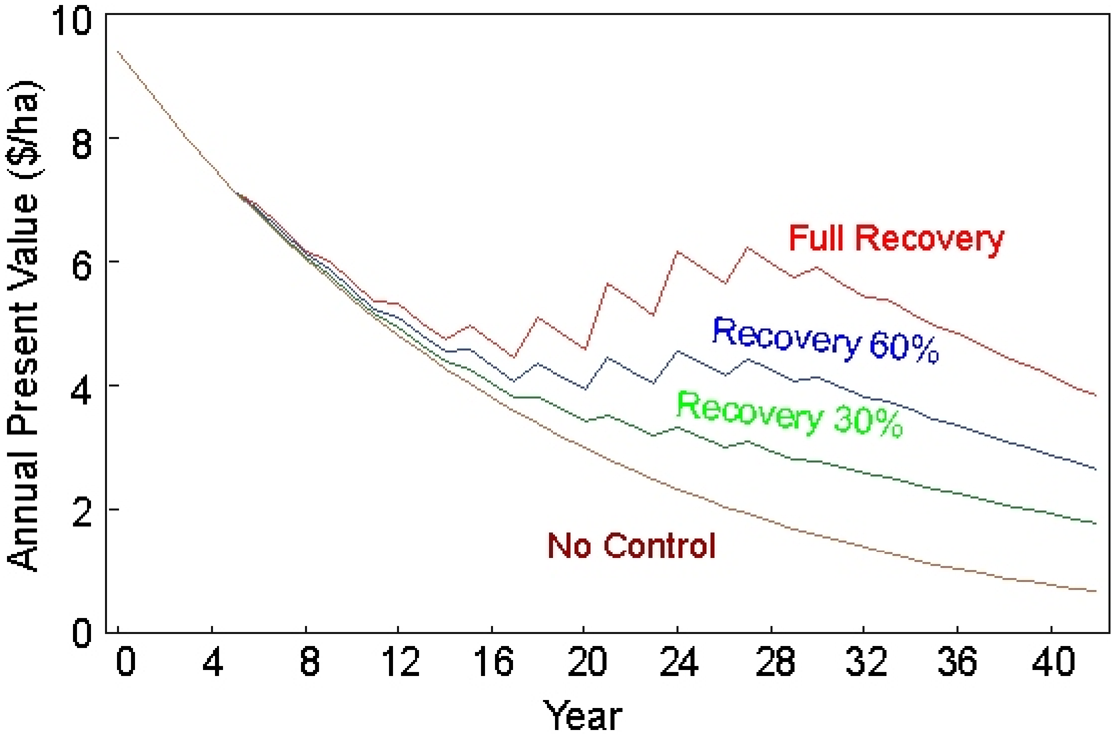

Figure 5. Annual present value for 40% weed cover, 2.0 AUM, and three levels of forage recovery, and no control.