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Supplementary Materials for

Saving endangered species using adaptive management

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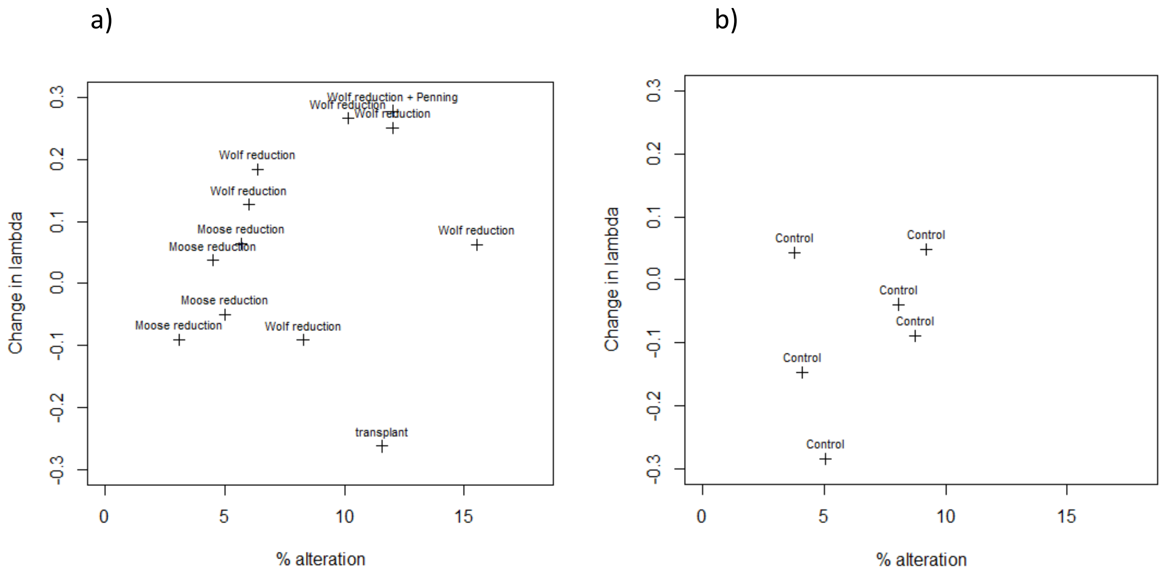


Fig. S1. The change in the caribou population growth rate (change in lambda; Δλ) as a result of the % of the woodland caribou range that was altered by early seral vegetation, a measure of habitat loss for caribou. An analysis of covariance accounting for this % habitat loss (logit link) on log transformed λ (i.e., *r*, instantaneous rate of increase) tested for the effects of treatment on caribou population trends. The slope was positive 0.12, with $p = 0.21$, and $r^2 = 0.039$. In contrast, the effect of treatments was significant, and $r^2 = 0.44$ (Table 1). The figure is divided into (a) treatment and (b) control populations to simplify visual interpretation.

Table S1. Population estimates, population growth rates (λ), and time spans of λ estimates for each caribou population. Also shown are treatment intensities, amount of disturbance by range (early seral vegetation), amount of forest loss and gain, leading forest type, and mean annual precipitation. For moose reductions, intensity refers to the percentage that the moose population was reduced from its peak, and for wolves, intensity refers to the mean no. removed/year/1000 km^2.

Study area	Abbre-viation	Population	Eco-type[a]	Range area (km^2)	Treatment	Percent disturbed	Dominant forest type[b]	2nd forest type[b]	Forest loss[c] (%)	Forest gain[c] (%)	Treatment intensity[d]	MAP[e]
REV	CON	Columbia North	S	4652.1	Moose reduction	5.7	ESSF	ICH	***2.9***	***2.8***	83%	1373
REV	COS	Columbia South	S	1691.4	Moose reduction	3.1	ESSF	ICH	2.0	1.1	83%	1396
REV	FBQ	Frisby-Boulder	S	691.7	Moose reduction	4.5	ESSF	ICH	3.0	1.4	83%	1403
REV	GRH	Groundhog	S	1006.0	Control	9.2	ESSF	ICH	***2.5***	***6.5***	n/a	1364
REV	WGS	Wells Gray South	S	3550.0	Control	3.8	ESSF	ICH	***1.3***	***2.4***	n/a	1397
SSE	SSE	South Selkirks	S	3887.8	Wolf reduction	8.3	ESSF	ICH	5.1	3.0	2.1	1407
PUS	PUS	Purcells South	S	771.5	Translocation	11.6	ESSF	ICH	5.9	5.6	n/a	766
PAR	HAS	Hart South	S	8080.9	Control	4.1	ESSF	SBS	***0.8***	***3.2***	n/a	1447
PAR	PAR	Parsnip	S	4279.0	Moose reduction	5.0	ESSF	SBS	***1.5***	***3.5***	40%	1331
PEACE	KSI	Kennedy Siding	C	2961.6	Wolf reduction	6.4	ESSF	SBS	3.9	2.4	7.2	1446
PEACE	SCE	Scott East	C	2215.0	Wolf reduction	6.3	ESSF	SBS	4.0	2.5	7.2	1188
PEACE	KZA	Klinse-za	C	3291.2	Wolf reduction	15.8	ESSF	SBS	11.0	5.1	7.2	1235
PEACE	KZA/ SCE[e]	Klinse-za/ Scott East	C	5506.2	Wolf reduction	12.0	ESSF	SBS			7.2	
PEACE	KZA/ SCE[e]	Klinse-za/ Scott East	C	5506.2	Wolf reduction	12.0	ESSF	SBS			7.2	
PEACE	QUI	Quintette	C	6078.1	Wolf reduction	10.2	ESSF	BWBS	7.6	2.5	7.2	902
PEACE	WOL	Wolverine	N	10541.2	Control	8.7	ESSF	SBS	5.6	3.0	n/a	771
PEACE	GRA	Graham	N	9290.8	Control	5.0	ESSF	BWBS	3.2	1.8	n/a	718
AB	RPC	Red Rock/ Prairie	C	4826.2	Control	8.0	Subalpine	UF	6.2	1.9	n/a	859
AB	ALP	À la Pêche	C	6614.9	Wolf reduction	6.0	Subalpine	Alpine			1.4	901
AB	ALP	À la Pêche	C	6614.9	Wolf reduction	6.0	Subalpine	Alpine	4.7	1.3	6.5	
AB	LSM	Little Smoky	Boreal	3086.1	Wolf reduction	15.5	UF	LF	11.4	4.2	9.8	667

			BEFORE TREATMENT					AFTER TREATMENT				
Abbrev-iation	**Population**	**Treatment**	**Year start**	**Year end**	**Population size: start**	**Population size: end**	**λ before treatment**	**Year start**	**Year end**	**Population size: start**	**Population size: end**	**λ after treatment**
CON	Columbia North	Moose reduction	1994	2004	206	129	0.95	2004	2013	129	152	1.02
COS	Columbia South	Moose reduction	1994	2004	114	40	0.90	2004	2013	40	6	0.81
FBQ	Frisby	Moose reduction	1994	2004	36	16	0.92	2004	2013	16	11	0.96
GRH	Groundhog	Control	1995	2004	37	16	0.91	2004	2013	16	11	0.96
WGS	Wells Gray South	Control	1995	2004	286	144	0.93	2004	2013	144	109	0.97
SSE	South Selkirks	Wolf reduction	2011	2014	36	14	0.73	2014	2018	18	3	0.64
PUS	Purcells South	Translocation	1994	2012	54	20	0.95	2012	2018	39	4	0.68
HAS	Hart South	Control	2002	2006	351	488	1.09	2010	2016	359	246	0.94
PAR	Parsnip	Moose reduction	2002	2007	146	148	1.00	2007	2016	199.5	129	0.95
KSI	Kennedy Siding	Wolf reduction	2007	2015	120	50	0.90	2015	2018	50	63	1.08
SCE	Scott East	Wolf reduction	2007	2013	22	20	0.98					
KZA	Klinse-za	Wolf reduction	1997	2013	191	16	0.86					
KZA/ SCE[f]	Klinse-za/ Scott East	Wolf reduction					0.86	2013	2014	36	40	1.11
KZA/ SCE[f]	Klinse-za/ Scott East	Wolf reduction + Penning					0.86	2014	2018	40	67	1.14
QUI	Quintette	Wolf reduction	2008	2016	173	54	0.86	2016	2018	54	69	1.13
WOL	Wolverine	Control	2008	2010	381	341	0.95	2016	2018	362	266	0.86
GRA	Graham	Control	2002	2015	282	114	0.93	2015	2016	114	74	0.65
RPC	Red Rock/ Prairie	Control	2004	2006	n/a	n/a	0.87	2007	2015	>50[g]		0.83

ALP	À la Pêche	Wolf reduction	2000	2006	n/a	n/a	0.97	2015	2017	>50[g]	1.10
ALP	À la Pêche	Wolf reduction	2007	2014	n/a	n/a	0.92	2015	2017	>50[g]	1.10
LSM	Little Smoky	Wolf reduction	2000	2006	n/a	n/a	0.91	2007	2017	110[h]	0.97

[a] The Southern Mountain population of Woodland Caribou is classified into three distinct groups based on ecological and evolutionary characteristics: southern (S), central (C), and northern (N). All populations in this study are Southern Mountain Woodland Caribou, except the Little Smoky range, which are Boreal Woodland Caribou (Boreal).

[b] ESSF is Engelmann Spruce—Alpine Fir, ICH is Interior Cedar—Hemlock, BWBS is Boreal White and Black Spruce, SBS is Sub-Boreal Spruce, LF is Lower Foothills, and UF is Upper Foothills.

[c] Based on Hansen et al. (2013) (1). ***Bold and italicized*** font indicate where forest gain is similar or greater than forest loss.

[d] Number of wolves removed/yr/km^2, OR, Percent that moose were reduced from the peak population.

[e] Mean Annual Precipitation (cm) for years 2001–2010.

[f] SCE and KZA caribou merged into a single population as the wolf reduction began.

[g] Based on minimum individuals observed during March recruitment surveys.

[h] 110 Based on DNA mark recapture in 2015.

Table S2. Analysis of covariance based on the null hypothesis that only habitat alteration explained the change in population growth rate (Δλ) (Fig. S1). The multiple R^2 is 0.095 and the adjusted R^2 is 0.039. Analysis was performed on *r*, where *r* = ln(λ).

	Estimate	SE	t- value	P-value
Intercept	-0.30	0.23	1.30	0.21
Habitat Alteration	0.11	0.088	1.30	0.21

Table S3. Analysis of covariance explaining the change in population growth rate (Δλ) based on recovery treatments for woodland caribou. Intercept represents the control populations. The multiple R^2 is 0.60 and the adjusted R^2 is 0.42. Analysis was performed on the change in *r*, where $r = \ln(\lambda)$. The ΔAICc relative to the top model (i.e., Table 1) is 4.68.

	Estimate	SE	t- value	P-value
Intercept	0.106	0.096	1.102	0.292
Treatment level:				
Moose reduction	0.184	0.092	1.992	0.070
Wolf reduction	0.312	0.168	1.856	0.088
Wolf reduction & Penning	-0.288	0.167	-1.731	0.109
Translocation	0.081	0.100	0.811	0.433
Habitat Alteration	0.106	0.096	1.102	0.292

Supplementary Information Text:

The Reliability of Population Growth Rate Estimates

Populations in Alberta (LSM, ALP, and RPC)

Annual λ values were based on estimates of adult female survival from telemetry studies and recruitment from aerial surveys in March (details and annual values are presented in (2-4)). The geometric mean of these estimates stratified by treatment and time period (i.e. before and after treatments began) were based on these annual λ estimates and are summarized in Fig. 1 and presented in Table S1. Hervieux et al. (3) reported that λ was significantly higher for the LSM population after the wolf removal treatment, while RPC (control) continued to decline. Here we show that ALP improved once the wolf reduction was expanded from the winter range to both the summer and winter range. Based on minimum counts during March recruitment surveys, the RPC and ALP populations were > 50 throughout the study, and LSM was estimated at 110 in 2015 based on fecal DNA analysis (5).

Populations in British Columbia – The Southern Mountain Ecotype

For the southern mountain populations (also referred to as the deep-snow ecotype; (6)), sightability was 88.2 % (135 out of 153 collared animals were detected), but when the snowpack was over 300 cm at 1900 m, 93 % (114 out of 123 collared animals were detected) when population surveys are done in late March (7). Only years when snow depth was > 300 cm were used for population estimates. With such high sightability, λ estimates will be robust to uncertainty, particularly since population decline has been so substantial. Based on > 25 years of radio telemetry and population genetics on adult females and males, as well as juveniles, these populations are demographically separated (8). More recent surveys did not have a marked sample because of the previously established relationship between sightability and snow depth, and radio-collaring animals of an endangered species comes with inherent risks, when non-invasive aerial surveys are possible without having to handle animals.

Columbia North (CON) – Moose reduction

The CON caribou population estimate in 2013 (n=152) was the minimum number observed and was higher than the upper 95% CI of the 2004 estimate of n=129 (95% CI: 129 – 143). Therefore, the conclusion that the population was at least stable (λ = 1.02) is supported, as described in (9).

Columbia South (COS) – Moose reduction

This caribou population was 114 (95% CI:106 – 142) in 1994, 40 in 2004 (3 of 3 collars detected; no CIs due to low number of marked animals) and the 2013 estimate was 6. Clearly a severe decline since 1994.

Frisby Queest (FBQ) – Moose reduction

The population was 36 in 1994 (1 of 2 collars observed) and the 2013 estimate was 11. Severe decline, and any uncertainty would not affect conclusions.

Wells Gray South (WGS) – Control

The population estimate was 286 in 1995 and 109 in 2013. No CIs are available for the southern portion of Wells Gray (a population that was found to be demographically separate from Wells Gray North; (6, 10), but over time for the entire Wells Gray population, 39 of 41 radio collared animals were detected during surveys.

Groundhog (GHG) – Control

A small population that has continued a trajectory of gradual decline (8, 9).

Hart South (HAS) – Control

Population trend was consistent with results of multiple intervening surveys all with high sightability (11).

Parsnip (PAR) – Moose reduction

Population trend was consistent with results of multiple intervening surveys all with high sightability (11).

South Selkirks (SSE) and Purcells South (PUS) – Wolf reduction and translocation

SSE was counted at 3 animals in March 2018, following a long period of gradual decline (8) – no other tracks were found after extensive searching. All 3 animals were captured and radio-collared following the survey and pregnancy tests revealed that all 3 were barren. The 20-year average for the Southern Mountain ecotype is 92% of adult females are pregnant (8). For PUS, all 20 animals translocated in 2012 were radio-collared and the fates of all animals was known (all died), and 4 animals were counted in 2018 – no other tracks were located after extensive searching.

Populations in British Columbia – The Central and Northern Mountain Ecotypes

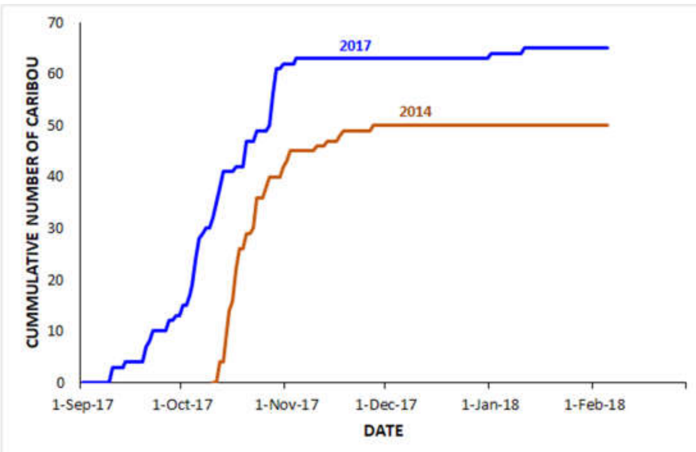
These populations are within a dryer climate typical of the Rocky Mountains (301 cm mean snowpack in March at 1450 m) meaning that sightability of woodland caribou is not as high as the southern group. Estimates include mark-resight correction factors from collared animals, camera trapping where individuals could be identified, or where animals were handled as part of maternity penning.

Scott East (SCE) and Klinse-Za (KZA) – Wolf reduction and safe haven (maternal penning)

This population has been periodically monitored by aerial surveys corrected for sightability since 1994. A high proportion (30-40%, annually since 2014) of these animals have been marked and handled as part of the maternal penning project. Although focused on KZA, maternal penning involved capture of cows from both SCE and KZA to mitigate risk to each population which were both relatively small (N = 20 and 16 in 2013 for SCE and KZA, respectively). Maternal penning of the mixed populations resulted in unpredictable range selection post-release and thereafter the herds merged and population estimates made for the combined herd areas (Table S1). Total population counts were possible due to the small number of animals and having collars placed in each group of caribou prior to surveys. Total count results were checked against sex-specific age-classes predicted using a calculation as follows $N_t = N_{t-1} + Calves_t - Mortalities_{(t-1,t)}$.

Kennedy Siding (KSI) – Wolf reduction

1993 estimate (n=97) was the minimum number observed. Estimates from periodic aerial survey counts, corrected for sightability, between 2002 and 2012 were consistent with a long-term decline. In 2014 and 2017 this population was monitored with cameras where all animals congregate on a winter range. Each animal was identified, based on antler characteristics, with most being detected numerous times. All radio-collared individuals were detected with cameras (n = 13). Below is the saturation curve of new animals, showing recent increase (12).



Quintette (QUI) – Wolf reduction

This population has been periodically monitored by aerial surveys corrected for sightability since 2002. Population estimates used for this analysis are consistent with the long-term trend line (12).

Wolverine (WOL) – Control

Aerial census and vital rates (survival and recruitment) both show a long-term decline of this control population (7).

Graham (GRA) - Control

This population has been periodically monitored by aerial surveys corrected for sightability since 1989. Population estimates used for this analysis are consistent with the long-term trend line (12).

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