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HEALTH SURVEY OF BOREAL CARIBOU (*RANGIFER TARANDUS CARIBOU*) IN NORTHEASTERN BRITISH COLUMBIA, CANADA

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ABSTRACT: Boreal woodland caribou (*Rangifer tarandus caribou*) are listed as threatened across Canada, and a basic understanding of their health status is lacking. From December 2012 to April 2013, we investigated multiple health indices for adult female boreal caribou (n=163) captured from seven herds in NE British Columbia, Canada. Health indices included physical characteristics, physiologic and trace mineral status, exposure to or infection with selected pathogens, and measures of chronic stress and inflammation, including serum amyloid A, haptoglobin, and hair cortisol concentration. Key findings were exposure to the bacterium *Erysipelothrix rhusiopathiae* in 14% of individuals, mild to severe hair loss associated with winter tick (*Dermacentor albipictus*) infestations in 76% of caribou from December to early February and 81% from late February to early April, and evidence of trace mineral deficiencies with 99% and 34% of individuals deficient in copper and selenium, respectively. Seroprevalence for exposure to selected pathogens was: alphaherpesvirus (63%), pestivirus (1%), *Besnoitia* spp. (60%), and *Neospora caninum* (2%). All animals were seronegative to *Brucella* spp. and *Toxoplasma gondii*. *Mycobacterium avium* ssp. *paratuberculosis* was not detected in any fecal samples. Parasite eggs or larvae, including *Parelaphostrongylus andersoni* (36%), *Skrjabinema* spp. (1%), Strongyle-type eggs (11%), *Moniezia*-type eggs (8%), and nematodirines (3%), were detected on fecal examination, but at low intensity. Blood biochemistry values and hair cortisol concentrations were within ranges previously reported in *Rangifer tarandus* sspp. Some significant differences among herds were noted, including antler morphology, exposure to *Besnoitia* spp., and concentrations of serum amyloid A, copper, cobalt, manganese, and iron.

Key words: Boreal caribou, parasitology, *Rangifer tarandus caribou,* serology, serum biochemistry, surveillance, trace minerals, wildlife health.

INTRODUCTION

Boreal woodland caribou (*Rangifer tarandus caribou*), referred to as boreal caribou hereafter, are found across the boreal forest ecoregions of Canada (Government of Canada 2017). They are classified as a Schedule 1 Threatened species under Canada's Species at Risk Act (Government of Canada 2017). Declines in populations have been widely attributed to habitat fragmentation, the creation of linear features (e.g., roads and seismic lines), and predation (Environment Canada 2012). Health determinants, such as infectious and noninfectious diseases, nutrition, and physiologic condition, can also influence the long-term sustainability of caribou populations (Macbeth and Kutz 2018). However, with few exceptions (Albon et al. 2002; Cuyler et al. 2012), the roles of these health determinants in caribou population dynamics are unknown (Carlsson et al. 2018).

In British Columbia (BC), Canada, boreal caribou occur only in the NE corner of the province and are in decline (Environment Canada 2012; Culling and Cichowski 2017). From December 2012 to July 2013, a higher than expected mortality of radio-collared, adult female, boreal caribou was observed in NE BC (Schwantje et al. 2014). In response, the Boreal Caribou Health Research Program was established in BC in 2013 by the BC Ministry of Forests, Lands, and Natural Resource Operations Wildlife Health Program.

Our objectives were to describe the diversity and prevalence or seroprevalence of selected bacteria, viruses, and parasites; to document other indices of health that are related to individual fitness, physiologic stress, inflammation, and trace mineral status in live-captured boreal caribou from all herds in NE BC; and to use this information to inform a health assessment framework that could be applied more broadly and consistently for caribou and other free-ranging ungulate species.

MATERIALS AND METHODS

Study area

The study area was described previously by Culling and Culling (2013). The study animals were from seven boreal caribou herds in NE BC (Fig. 1). The herds occupied distinct ranges that varied in size from 752 to 13,897 km^2 and included the Chinchaga, Snake-Sahtaneh, Calendar, Maxhamish, Prophet, and Parker ranges, as well as Fort Nelson, which has been identified as "an area of interest, with current status unknown" (British Columbia Ministry of the Environment 2010; Culling and Cichowski 2017). The total population size of boreal caribou in 2012 was estimated to range from 1,290 to 1,360 individuals across all herd ranges: Maxhamish, *n*=300; Calendar, *n*=290; Snake-Sahtaneh, *n*=360; Chinchaga, *n*=250; Parker, *n*=40–60; and Prophet, *n*=50–100 (Environment Canada 2012). Environment Canada (2012) found the percentage of anthropogenic habitat disturbance, defined as any human-caused disturbance to the landscape buffered at 500 m, to be high across all of the herd ranges: Maxhamish (57%), Parker (57%), Calendar (58%), Chinchaga (74%), Prophet (77%), and Snake-Sahtaneh (86%).

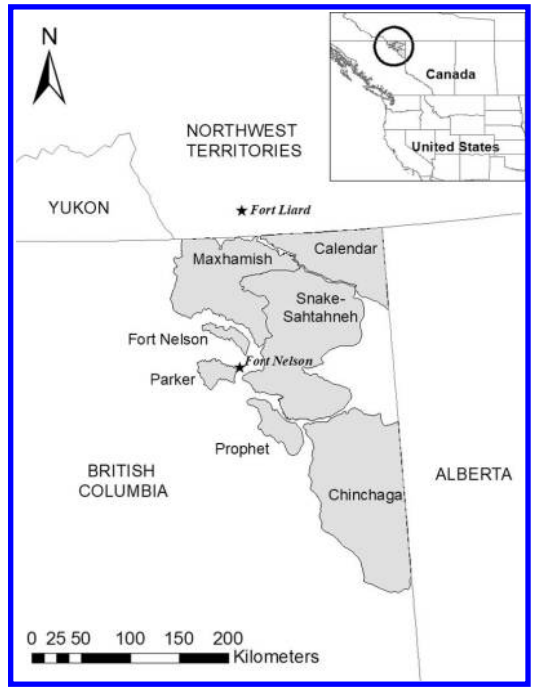

FIGURE 1. Map of the boreal caribou (*Rangifer tarandus caribou*) herds in NE British Columbia, Canada.

Live animal sampling

Biological samples were collected from 163 adult female boreal caribou from the seven herds from 17 December 2012 to 1 April 2013. Caribou were captured by net gun from a helicopter as part of a long-term monitoring project in which 15% of the estimated population from each herd was captured and radio-collared (Culling and Culling 2013). Active chase times per individual, defined as the number of seconds an individual was running intensively from the helicopter before net gunning, varied from 20 to 90 s. Total processing time from capture and sampling to release was 15–20 min. All caribou capture, sampling, and handling methods complied with the BC Resources Inventory Standards Committee Guidelines (RISC 1998a, b) and were approved by the BC Ministry of Forests, Lands, and Natural Resource Operations Animal Care Committee (Permit FJ12-83091) and permitted under the BC Wildlife Act.

Physical characteristics

Captured individuals were assigned into broad, sometimes overlapping, age classes based on body size, antler configuration, and incisor wear (Culling and Culling 2016). For analyses, caribou were

classified into three age classes: young adult (2–5 yr), mature adult (4–8 yr), and old adult (≥8 yr). Body size measurements, antler class, residual velvet on antlers, and presence of calf at heel were recorded, and the loss and breakage of hair was photographed. The amount of hair loss on each caribou was scored into five categories (none, mild, moderate, severe, and extreme) using a methodology described by Culling and Culling (2016). Presence of physical anomalies (e.g., deformities, growths, and lesions) were recorded and photographed. Presence of warble fly (*Hypoderma tarandi*) larvae was determined by visual inspection and palpation of the skin of the dorsum.

Sample collection and analysis

Blood and hair samples were collected from all individuals. Fecal samples and ticks were collected if present. Within 7–10 min after capture, at least 20 mL of blood was collected from the cephalic vein into three serum tubes and two ethylenediaminetetraacetic acid (EDTA) tubes. The EDTA blood was held at 4 C, and two to four blood smears were made at the end of each day and stored at room temperature. Serum blood tubes were spun at 1,286 × G, 2–10 h after sample collection with an IEC Spinette centrifuge (Damon/IEC Division, Needham Heights, Massachusetts, USA), and the serum was stored at –20 C until analysis. Fecal pellets were collected from the anus when present or fresh off the ground within 7–20 min after capture and stored at –20 C until analysis. If ticks were collected, half were stored frozen at –20 C and half in 70% ethanol at room temperature. Hair samples were plucked from the shoulder and stored dry at room temperature in a paper envelope in the dark. All samples were kept in an insulated pack while in the field.

Pathogens and other indices of caribou health were chosen for testing based on a review of the literature of caribou and reindeer (*Rangifer tarandus* sspp.), hereafter referred to as *Rangifer*, and other cervid species. Input from biologists, wildlife veterinarians, and other stakeholders working with these species in NE BC and elsewhere was used as well. Pathogens and health indices that had the potential to affect caribou survival and reproduction were prioritized.

Helminth eggs were identified to the lowest taxonomic level possible. To identify the species of protostrongylid nematode dorsal-spined larvae (DSLs) detected, six fecal samples testing positive for DSL were randomly selected, and PCR and DNA sequencing were run on five DSLs per sample (see Supplementary Materials). Blood smears were examined microscopically for hemoparasites. Ticks were identified on the basis of morphology by the Canadian Wildlife Health Cooperative (Calgary, Alberta, Canada). Additional details regarding laboratory methods are in the Supplementary Materials.

Data analyses

Results were presented and statistically analyzed at the herd level for only the Calendar, Chinchaga, Maxhamish, and Snake-Sahtaneh herds, because fewer than 10 caribou were sampled from each of the Parker (n=9), Prophet (n=5), and Fort Nelson (n=3) herds. The intensity of parasite eggs and larvae in feces was quantified on the basis of infected individuals only. Neck size; hair loss, which was presumed to be from winter tick infestations (Welch et al. 1990); and concentrations of trace minerals can vary seasonally (Reimers 1983; Mooring and Samuel 1998; Duffy et al. 2009). Thus, we analyzed these parameters by early (17 December–15 February) and late (16 February–1 April) winter capture dates. We grouped the only two extreme cases of hair loss with severe cases of hair loss for analysis.

Twenty-nine percent (46/161) of the serum samples had pestivirus optical density (OD) values classified by the manufacturer to be doubtful. The cutoff point for the *Erysipelothrix rhusiopathiae* enzyme-linked immunosorbent assay was determined for *Rangifer* by creating a mixture distribution analysis and bootstrapped confidence intervals around the cutoff as described by Garnier et al. (2017). We classified *E. rhusiopathiae* OD values that fell within the bootstrapped confidence interval to be borderline. All animals with borderline or doubtful results were classified as negative in the analysis. This approach increased the specificity of the test but may have reduced sensitivity. To compare our biochemistry results with those from 104 free-ranging boreal caribou reported by Johnson et al. (2010), we calculated the central 95% fraction (Solberg 1987). Statistical analyses comparing biochemical parameters by herd were conducted only for the parameters that were not within range of those reported by Johnson et al. (2010).

The means ±1 SD were calculated for continuous data with a normal distribution, and the median and interquartile range were calculated for continuous data that were not normally distributed. Prevalence or seroprevalence and 95% confidence interval (CI) were calculated for binary and categorical data. To analyze continuous data, one-way analysis of variance (ANOVA), Welch's ANOVA, Kruskal-Wallis, or Mann-Whitney *U*-test were used where appropriate and calculated in SPSS (Version 24.0, IBM, Armonk, New York, USA). Exact logistic regression was used to analyze binary data in STATA (Version 14.2, StataCorp LLC, College Station, Texas,

TABLE 1. Age, reproductive, and antler characteristics of live-captured adult female boreal caribou (*Rangifer tarandus caribou*) from seven herds in NE British Columbia, Canada, in winter 2012–2013. Results are presented at the herd level only for herds that had a sample size of 10 or more animals.

		% Prevalence (95% CI)[a]				
Parameter	Category	Calendar (*n*=27)	Chinchaga (*n*=37)	Maxhamish (*n*=24)	Snake-Sahtaneh (*n*=56)	All seven herds (*n*=163)
Age class	Young adult	44 (25–65)	51 (34–68)	33 (16–55)	41 (28–55)	42.9 (35.2–50.9)
	Mature adult	30 (14–50)	27 (14–44)	38 (19–59)	39 (26–53)	34.4 (27.1–42.2)
	Old adult	26 (11–46)	22 (10–38)	29 (13–51)	20 (10–32)	22.7 (16.5–29.9)
Pregnant	Yes	85 (66–96)	86 (71–95)	75 (53–90)	84 (72–92)	82.8 (76.1–88.3)
	No	15 (4–34)	14 (4–29)	21 (7–42)	16 (8–28)	16.6 (11.2–23.2)
	Not tested	—[b]	—	4 (0.1–21)	—	0.6 (0.02–3.4)
Calf at heel	Yes	26 (11–46)	22 (10–38)	50 (29–71)	21 (12–34)	24.5 (18.1–31.9)
	No	70 (50–86)	78 (62–90)	50 (29–71)	73 (60–84)	72.4 (64.9–79.1)
	Not determined	4 (0.1–19)	—	—	5 (1–15)	3.1 (1.0–7.0)
Antler class	None	11 (2–29)	0 (0–10)	4 (0.1–21)	7 (2–17)	6.7 (3.4–11.8)
	Spike	0 (0–13)	5 (0.7–18)	4 (0.1–21)	2 (0–10)	2.4 (0.7–6.2)
	Small branched	15 (4–34)	19 (8–35)	38 (19–59)	27 (16–40)	23.9 (17.6–31.2)
	Medium branched	33 (16–54)	30 (16–47)	29 (13–51)	43 (30–57)	35.6 (28.2–43.4)
	Large branched	4 (0.1–19) A[c]	24 (12–41) B	4 (0.1–21) AB	14 (6–26) AB	13.5 (8.6–19.7)
	Atypical	37 (19–58) A	22 (10–38) AB	21 (7–42) AB	7 (2–17) B	17.8 (12.2–24.5)
Residual velvet	Yes	18 (6–38)	16 (6–32)	25 (10–47)	18 (9–30)	17.2 (11.7–23.9)
	No	67 (46–84)	81 (65–92)	71 (49–87)	75 (62–86)	75.5 (68.1–81.8)
	Not applicable	15 (4–34)	3 (0.1–14)	4 (0.1–21)	7 (2–17)	7.4 (3.9–12.5)

[a] When proportion was 0, the one-sided 95% confidence interval (CI) was calculated.

[b] — = not applicable.

[c] Proportions within a row followed by different capital letters are significantly different from each other ($P \leq 0.05$).

USA). To determine whether outcomes with more than two categories (e.g., hair loss category and age class) differed by herd, we used ordered logistic regression if the proportional odds assumption was met. Otherwise, we used generalized ordered logistic regression. The significance level for all analyses was set to α=0.05. Missing data were excluded from each analysis. Additional details regarding the statistical analyses are in the Supplementary Materials. The map of the study area was generated by ArcMap GIS (Version. 10.1, Esri, Redlands, California, USA) with the Province of British Columbia (2017) and Provincial Boundaries Area (Natural Resources Canada, Instituto Nacional de Estadística Geografía e Informática, and the US Geological Survey 2006) data layers.

RESULTS

Physical characteristics

Physical anomalies were noted in four caribou in the Maxhamish herd, described as a supernumerary teat (*n*=2), absence of all four teats (*n*=1), an abnormally shaped nostril (*n*=1), and a 2-cm skin mass on the flank (*n*=1). Age class, pregnancy status, and presence of residual antler velvet did not vary by herd (Table 1; see Supplementary Material Table S1). Caribou in the Maxhamish herd were more likely to have a calf at heel than the Chinchaga and Snake-Sahtaneh herds (odds ratio [OR]=3.35, 95% CI=1.03–12.9; OR=3.36, 95% CI=1.08–10.8, respectively), but the overall model was not significant (Table 1; see Supplementary Material Table S1). Large branched antlers were significantly more likely in the Chinchaga than the Calendar herd (OR=8.14, 95% CI=1.01–380; Table 1; see Supplementary Material Table S1), whereas atypical antlers were significantly more likely in the Calendar than Snake-Sahtaneh herd (OR=7.4, 95% CI=1.8–36.8; Table 1; see Supplementary Material Table

TABLE 2. Early and late winter hair loss scores of live-captured adult female boreal caribou (*Rangifer tarandus caribou*) from seven herds in NE British Columbia, Canada, in 2012–2013. Results are presented at the herd level only for herds that had a sample size of 10 or more animals. None of the proportions at the herd level within each row were significantly different from each other ($P \leq 0.05$).

	% Prevalence (95% CI)[a]				
	Calendar	Chinchaga	Maxhamish	Snake-Sahtaneh	All seven herds
Early winter	*n*=0	*n*=30	*n*=19	*n*=29	*n*=94
None	ND[b]	33 (17–53)	37 (16–62)	17 (6–36)	25 (16–35)
Mild	ND	47 (28–66)	16 (3–40)	48 (29–68)	41 (31–51)
Moderate	ND	17 (6–35)	47 (24–71)	34 (18–54)	33 (24–44)
Severe	ND	3 (0.1–17)	0 (0–18)	0 (0–11.9)	1 (0–6)
Late winter	*n*=27	*n*=7	*n*=5	*n*=27	*n*=70
None	15 (4–34)	29 (4–71)	0 (0–52)	22 (9–42)	19 (10–30)
Mild	26 (11–46)	29 (4–71)	60 (15–95)	26 (11–46)	30 (20–42)
Moderate	37 (19–58)	29 (4–71)	20 (0.5–72)	30 (14–50)	31 (21–44)
Severe	22 (9–42)	14 (0.4–58)	20 (0.5–72)	22 (9–42)	20 (11–31)

[a] When proportion was 0, the one-sided 95% confidence interval (CI) was calculated.
[b] ND = no data collected.

S1). Caribou without antlers were not observed in the Chinchaga herd (Table 1).

No differences by herd were found in mean neck circumference or metatarsal, hindfoot, and mandible lengths (see Supplementary Material Tables S2 and S3). Mild to severe hair loss was observed in 76% of caribou in early winter, and 81% in late winter. Hair loss was observed in all herds, but hair loss scores did not differ significantly by herd in either early or late winter (Table 2; see Supplementary Table S1). Overall, severe hair loss was observed in 1% of individuals in early winter and 20% of individuals in late winter (Table 2).

Sera, blood slides, feces, and hair samples were analyzed for selected bacteria, viruses, protozoa, helminths, biochemical parameters, trace minerals, hair cortisol concentration, and pregnancy (Table 3; see Supplementary Material Table S4).

Pathogens

Anti-*Brucella* spp. antibodies were not detected in any of the samples (Table 4). All herds were positive for exposure to *E. rhusiopathiae*, but seroprevalence did not differ by herd (Table 4; see Supplementary Material Table S1). *Mycobacterium avium* ssp. *paratuberculosis* was not detected in any of the herds for which fecal samples were tested (*n*=36; three from Calendar, eight from Chinchaga, three from Maxhamish, three from Prophet, and 19 from Snake-Sahtaneh).

Seroprevalence did not differ by herd for alphaherpesvirus (Table 4; see Supplementary Material Table S1). One serum sample was seropositive to pestivirus (Table 4). Virus neutralization indicated that this virus was not bovine viral diarrhea virus (BVDV).

Caribou in all herds were seropositive to *Besnoitia* spp. (Table 4). Seroprevalence differed significantly among herds and was higher in the Chinchaga than Calendar and Snake-Sahtaneh herds (OR=8.0, 95% CI=1.94–38.73; OR=4.6, 95% CI=1.45–17.5, respectively; Table 4; see Supplementary Material Table S1). Only three individuals overall tested positive to *Neospora caninum*, and no individuals tested seropositive to *Toxoplasma gondii* (Table 4). No hemoparasites were detected in blood smears (*n*=16; one from Calendar, two from Chinchaga, four from Maxhamish, and nine from Snake-Sahtaneh).

Fecal samples were collected from 159 individuals. No trematode eggs, including those of the giant liver fluke (*Fascioloides*

TABLE 3. Diagnostic tests employed and references for bacteria, viruses, protozoans, helminths, and other health parameters for serum, fecal, and hair samples collected from live-captured adult female boreal caribou (*Rangifer tarandus caribou*) in NE British Columbia, Canada, in winter 2012–2013.

Pathogen or health index	Sample type	Test (manufacturer)	Reference for laboratory methods used[a]
Bacteria			
Brucella spp.	Serum	Indirect ELISA based on chimeric protein A/G[b]	Nymo et al. (2013)[c]
Erysipelothrix rhusiopathiae	Serum	Indirect ELISA[b]	None[d]
Mycobacterium avium ssp. *paratuberculosis*	Feces	IS900 and F57 quantitative PCR with an a posteriori selective fecal culture using MagMAX Total Nucleic Acid Isolation Kit (Applied Biosystems, Carlsbad, California, USA)	Eisenberg et al. (2010); Ford et al. (2013)[c]
Viruses			
Alphaherpesvirus	Serum	LSIVet Bovine IBR gB Blocking ELISA (Life Technologies Inc., Paris, France)	das Neves et al. (2009)[c]
Pestivirus	Serum	SERELISA BVD p80 Ab Monoblocking Kit (Synbiotics Corporation, Lyon, France) and virus neutralization assay[b] for BVDV on positive sample	Kautto et al. (2012)[c]
Protozoa			
Besnoitia spp.	Serum	Indirect ELISA with a posteriori western blot[b]	Gutiérrez-Expósito et al. (2012)[c]
Neospora caninum	Serum	Indirect ELISA with a posteriori western blot[b]	Gutiérrez-Expósito et al. (2012)[c]
Toxoplasma gondii	Serum	ID Screen Toxoplasmosis Indirect Multispecies ELISA Kit (Innovative Veterinary Diagnostics, Grabels, France)	None
Helminths			
Gastrointestinal nematode, cestode, and coccidian oocysts and eggs	Feces	Wisconsin double centrifugation sucrose flotation	Cox and Todd (1962)
Protostrongylid nematode larvae	Feces	Modified Baermann technique and PCR and DNA sequencing on six positive samples	Forrester and Lankester (1997)[c]; Kafle et al. (2015)
Trematode eggs	Feces	Fecal sedimentation (Flukefinder, Soda Springs, Idaho, USA)	None
Other Parameters			
Serum biochemistry[e]	Serum	Photometric (±calculated) tests (Roche Diagnostics, Indianapolis, Indiana, USA) using bovine clinical diagnostic panel[b]	None
Serum amyloid A	Serum	Tridelta Phase Serum Amyloid-A Multispecies ELISA Kit (Tridelta Development Ltd., Boonton, New Jersey, USA)	None[f]
Trace minerals[g]	Serum	Inductively coupled plasma mass spectrometry using Bruker 820 MS (Bruker Ltd., Milton, Ontario, Canada)	None

TABLE 3. Continued.

Pathogen or health index	Sample type	Test (manufacturer)	Reference for laboratory methods used[a]
Hair cortisol concentration	Hair	Oxford EA-65 Cortisol Competitive EIA kit (Oxford Biomedical, Lansing, Michigan, USA)	Ashley et al. (2011)[c]; Macbeth (2013)[c]
Pregnancy	Serum	ELISA test measuring pregnancy-specific protein B (BioPRYN wild test, BioTracking Inc., Moscow, Idaho, USA)	None

[a] Laboratories that conducted tests are in Supplementary Material Table S4.

[b] In-house assay used. ELISA = enzyme-linked immunosorbent assay; BVD = bovine viral diarrhea; BVDV = bovine viral diarrhea virus.

[c] Study-validated test in *Rangifer tarandus* sspp.

[d] Bondo et al. (2018)–validated test in *R. tarandus* sspp.

[e] Includes calcium, phosphorus, calcium:phosphorous ratio, magnesium, sodium, potassium, sodium:potassium ratio, chloride, carbon dioxide, anion gap, total protein, albumin, globulin, albumin:globulin ratio, urea, creatine, glucose, cholesterol, total bilirubin, conjugated bilirubin, free bilirubin, alkaline phosphatase, gamma-glutamyltransferase, aspartate aminotransferase, creatine kinase, glutamate dehydrogenase, nonesterified fatty acids, beta-hydroxybutyrate, and haptoglobin.

[f] Orro et al. (2004)– and Orro (2008)-validated test in *R. tarandus* sspp.

[g] Includes copper, cobalt, iron, manganese, molybdenum, selenium, and zinc.

magna), were detected in any of the samples (see Supplementary Material Table S5). Protostrongylid DSL prevalence at the herd level ranged from 26% to 51% (see Supplementary Material Table S5) but did not differ significantly by herd (see Supplementary Material Table S1). Intensity of DSL was low for all herds, ranging from 0.5 to 7.7 larvae/g of feces, and did not differ significantly by herd (see Supplementary Material Table S5). Dorsal spined larvae from six fecal samples were identified by DNA sequencing as *Parelaphos-*

TABLE 4. Seroprevalence of bacteria, viruses, and protozoa in adult live-captured female boreal caribou (*Rangifer tarandus caribou*) in winter 2012–2013 in NE British Columbia, Canada. Results are presented at the herd level only for herds that had a sample size of 10 or more animals.

	% Seroprevalence (95% CI)[a]									
Pathogen	*n*	Calendar	*n*	Chinchaga	*n*	Maxhamish	*n*	Snake-Sahtaneh	*n*	All seven herds
Bacteria										
Brucella spp.	27	0 (0–13)	36	0 (0–10)	23	0 (0–15)	56	0 (0–5)	161	0 (0–2.3)
Erysipelothrix rhusiopathiae[b]	27	18 (6–38)	36	3 (0–14)	23	13 (3–34)	56	16 (8–28)	161	13.7 (8.8–20.0)
Viruses										
Alphaherpesvirus	27	59 (40–78)	36	69 (52–84)	23	56 (34–77)	56	64.3 (50–77)	161	62.7 (54.8–70.2)
Pestivirus[c]	27	0 (0–13)	36	0 (0–10)		4 (0.1–22)		0 (0–5)		0.6 (0.02–3.4)
Protozoa										
Besnoitia spp.	20	40 (19–64) B[d]	33	85 (68–95) A	23	70 (47–87) AB	55	56 (42–70) B	148	60.8 (52.4–68.7)
Neospora caninum	21	5 (0.1–24)	34	3 (0.1–15)	23	0 (0–15)	55	0 (0–6)	151	2.0 (0.41–5.7)
Toxoplasma gondii	26	0 (0–13)	37	0 (0–10)	23	0 (0–15)	56	0 (0–6)	161	0 (0–2.3)

[a] When proportion was 0, the one-sided 95% confidence interval (CI) was calculated.

[b] Borderline results were found in one animal each from Calendar and Snake-Sahtaneh, two animals from Chinchaga, no animals in Maxhamish, and three animals overall from the other three herds. These were considered negative in calculating seroprevalence.

[c] Doubtful results were found in 14 animals from Calendar, five animals each from Chinchaga and Maxhamish, 24 animals from Snake-Sahtaneh, and one animal each from the other three herds. These were considered negative in calculating seroprevalence.

[d] Seroprevalences within a row followed by capital letters are significantly different from each other ($P \leq 0.05$).

TABLE 5. Serum biochemical parameters for adult female boreal caribou (*Rangifer tarandus caribou*) live-captured in winter 2012–2013 in NE British Columbia (NE BC), Canada, in this study compared with adult female boreal caribou captured by net-gunning in 2003–2006 in the Northwest Territories (NT), Canada (Johnson et al. 2010). Means (SD) were reported when the parameter was normally distributed and medians (interquartile range, IQR) were reported when parameters were not normally distributed.

Parameter (unit)	NE BC caribou (n=81)			NT caribou (n=104)		
	Range[a]	Mean (SD)	Median (IQR)	Range	Mean (SD)	Median (IQR)
Calcium (mmol/L)	2.24–2.74	—[b]	2.49 (2.44–2.56)	1.64–3.15	—	2.64
Phosphorus (mmol/L)	1.29–2.75	2.0 (0.36)	—	0.73–2.53	1.7 (0.42)	—
Calcium:phosphorus ratio	0.88–1.81	—	1.2 (1.10–1.45)	ND[c]	ND	ND
Magnesium (mmol/L)	0.90–1.20	—	1.1 (1.00–1.10)	0.62–1.40	1.1	—
Sodium (mmol/L)	125–150	—	143 (139–146)	93–170	—	146
Potassium (mmol/L)	3.7–28.1	—	5.6 (4.4–10.5)	3.0–8.0	—	4.3
Sodium:potassium ratio	4–40	—	26 (13–33)	ND	ND	ND
Chloride (mmol/L)	87–99	—	95 (92–97)	55–106	—	94
Bicarbonate (mmol/L)	2–12	—	6 (4–8)	4–17	—	8
Anion gap (mmol/L)	41–61	50 (6.0)	—	ND	ND	ND
Urea (mmol/L)	1.0–2.5	—	1.3 (1.1–1.7)	1.0–4.3	—	1.8
Creatinine (μmol/L)	158–276	210 (33.5)	—	123–294	212 (40)	—
Glucose (mmol/L)	3.2–10.3	6.7 (1.9)	—	4.1–13.0	8.3 (2.4)	—
Calcium osmolarity (mmol/L)	278–296	—	289 (284–291)	ND	ND	ND
Cholesterol (mmol/L)	0.86–1.56	1.2 (0.20)	—	ND	ND	ND
Nonesterified fatty acids (mmol/L)	0.20–1.60	—	0.60 (0.40–0.90)	ND	ND	ND
Total protein (g/L)	62–83	70 (5.4)	—	45–86	71 (8.8)	71
Albumin (g/L)	36–47	43 (2.9)	—	28–46	39 (4.0)	39
Globulin (g/L)	20–41	—	26 (24–31)	17–45	32 (6.4)	—
Albumin:globulin ratio	1.00–2.2	1.6 (0.34)	—	0.89–1.77	—	1.2
Total bilirubin (μmol/L)	1–3	—	1 (1–2)	0.53–5	2.5 (0.96)	—
Conjugated bilirubin (μmol/L)	0–1	—	1 (1–1)	ND	ND	ND
Free bilirubin (μmol/L)	0–3	—	0 (0–1)	ND	ND	ND
Alkaline phosphatase (U/I)	27–110	—	55 (39–67)	ND	ND	ND
Aspartate aminotransferase (U/I)	40–119	—	69 (58–83)	42–163	—	77
Gamma-glutamyltransferase (U/I)	1–64	—	17 (10–24)	ND	ND	ND
Beta-hydroxybutyrate (U/I)	338–844	585 (140)	—	ND	ND	ND
Glutamate dehydrogenase (U/I)	1–11	—	2 (1–3)	ND	ND	ND
Creatine kinase (U/I)	79–462	—	206 (146–313)	96–1614	ND	286

[a] 2.5–95.5 percentile.

[b] — = not applicable.

[c] ND = no data collected.

trongylus andersoni, the caribou muscle worm.

Pinworm (*Skrjabinema* spp., presumably *tarandi*) eggs were identified in one sample from Snake-Sahtaneh (see Supplementary Material Table S5). The overall prevalence of strongyle, nematodirine, and *Moniezia* eggs in the subset of 36 fecal samples tested was 11%, 3%, and 8%, respectively, and intensity was low (see Supplementary Material Table S5). Coccidia oocysts were not found in any of the samples tested (see Supplementary Material Table S5). There was no evidence of subcutaneous larvae of warble flies. Ticks were collected from six caribou and identified as *Dermacentor albipictus*, the winter tick.

TABLE 6. Serum amyloid A, haptoglobin, and hair cortisol concentration from adult female boreal caribou (*Rangifer tarandus caribou*) live-captured in winter 2012–2013 in NE British Columbia, Canada, in this study and compared with free-ranging barren-ground caribou (*Rangifer tarandus groenlandicus*) in Greenland (Macbeth 2013). Results are presented at the herd level only for herds that had a sample size of 10 or more animals.

	Median (interquartile range)									Mean (range)
Parameter	*n*	Calendar	*n*	Chinchaga	*n*	Maxhamish	*n*	Snake-Sahtaneh	*n*	All seven herds	Barren-ground caribou (*n*=48)
Serum amyloid A (μg/mL)	27	94.7 (75.2–125.2) A[a]	37	26.7 (19.9–44.9) B	23	45.7 (20.2–96.0) B	55	54.3 (26.4–81.8) B	161	48.3 (21.6–94.7)	NT[b]
Haptoglobin (g/L)	23	0.15 (0.14–0.19)	34	0.15 (0.14–0.16)	23	0.14 (0.14–0.15)	53	0.15 (0.14–0.17)	151	0.15 (0.14–0.16)	NT
Hair cortisol concentration (pg/mg)	27	1.21 (0.95–2.63)	36[c]	1.20 (0.88–2.73)	24	1.33 (0.85–2.12)	56	1.67 (1.11–3.67)	162	1.52 (0.96–2.63)	2.26 (1.21–3.87)

[a] Medians within a row followed by capital letters are significantly different from each other ($P \leq 0.05$).

[b] NT = not tested.

[c] One animal had values below the detection limit and was excluded from the analysis.

Biochemical parameters, trace minerals, and hair cortisol concentration

Thirteen of 17 (76%) of the serum biochemical parameters tested in this study were within the ranges reported for adult female boreal caribou captured by net-gun in the Northwest Territories (NT), Canada (Johnson et al. 2010; Table 5). The potassium, phosphorus, albumin, and albumin:globulin ratio levels of the caribou from NE BC were above the ranges reported from the NT for 31% (25/81), 5% (4/81), 6% (5/81), and 28% (23/81) of individuals, respectively. Individuals from all herds had potassium or albumin:globulin ratio levels, or both, above the ranges reported from the NT. The high levels of both of these biochemical parameters were observed in both early and late winter captures. Potassium levels differed significantly by herd and were higher in the Chinchaga (median, interquartile range: 8.0, 5.1–12.9 mmol/L) and Snake-Sahtaneh (6.7, 5.4–13.6 mmol/L) than the Calendar (4.4, 3.8–4.8 mmol/L) herd (see Supplementary Material Table S3). Phosphorus, albumin, and albumin:globulin ratios did not differ by herd (see Supplementary Material Table S3). Serum amyloid A (SAA) levels differed significantly by herd and were higher in the Calendar compared with the other herds (Table 6; see Supplementary Material Table S3). Haptoglobin levels did not differ among herds (Table 6; see Supplementary Material Table S3).

Copper and selenium levels for 98% and 34%, respectively, of the individuals from all herds were below the minimum range reported for 100 *Rangifer* by Puls (1994). Significant differences were found among herds for copper, cobalt, manganese, and zinc levels in early winter (Table 7; see Supplementary Material Table S3) and for cobalt, iron, and manganese in late winter (Table 8; see Supplementary Material Table S3). In the early winter statistical analysis for manganese, we removed one extreme outlier of 4.8 ppm from the Maxhamish herd because it was far out of range, was potentially a laboratory error, and had a significant effect on the model (see Supplementary Material Table

TABLE 7. Serum trace minerals from adult female boreal caribou (*Rangifer tarandus caribou*) live-captured in early winter 2012–2013 in NE British Columbia, Canada, in this study and compared with reindeer and caribou (*R. tarandus* sspp.) from Puls (1994). Results are presented at the herd level only for herds that had a sample size of 10 or more animals.

Trace minerals	Median (interquartile range) (μg/mg)				Range[a]
	Chinchaga (n=29)	Maxhamish (n=15)	Snake-Sahtaneh (n=28)	All six herds[b] (n=86)	Reindeer and caribou (n=100)
Cobalt	7.0×10^{-4} (5.9×10^{-4}–8.2×10^{-4}) A[c]	4.2×10^{-4} (3.4×10^{-4}–4.8×10^{-4}) B	4.6×10^{-4} (4.2×10^{-4}–5.2×10^{-4}) B	4.9×10^{-4} (4.4×10^{-4}–6.5×10^{-4})	NE[d]
Copper	5.1×10^{-4} (4.6×10^{-4}–5.7×10^{-4}) A	4.1×10^{-4} (2.5×10^{-4}–4.4×10^{-4}) B	4.4×10^{-4} (3.6×10^{-4}–4.7×10^{-4}) B	4.6×10^{-4} (4.0×10^{-4}–5.3×10^{-4})	7.0×10^{-4}– 0.0018
Iron	0.0043 (0.0035–0.0077)	0.0036 (0.0028–0.0041)	0.0045 (0.0033–0.0053)	0.0040 (0.0032–0.0052)	NE
Manganese	5.1×10^{-6} ($4.2\text{x}10^{-6}$–6.0×10^{-6}) A	4.1×10^{-6} (3.3×10^{-6}–5.3×10^{-6}) B	4.2×10^{-6} (3.4×10^{-6}–5.1×10^{-6}) AB	4.5×10^{-6} (3.7×10^{-6}–5.5×10^{-6})	NE
Molybdenum[e]	1.7×10^{-6} (9.5×10^{-7}–2.8×10^{-6})	1.4×10^{-6} (1.3×10^{-6}–1.4×10^{-6})	1.1×10^{-6} (9.0×10^{-7}–1.2×10^{-6})	1.2×10^{-6} (9.5×10^{-7}–2.1×10^{-6})	NE
Selenium	5.3×10^{-5} (4.9×10^{-5}–5.7×10^{-5})	5.0×10^{-5} (4.3×10^{-5}–5.5×10^{-5})	4.8×10^{-5} (4.5×10^{-5}–5.4×10^{-5})	5.1×10^{-5} (4.8×10^{-5}–5.5×10^{-5})	5.0×10^{-5}–1.4×10^{-4}
Zinc	0.0011 (9.0×10^{-4}–0.0013)	8.2×10^{-4} (7.1×10^{-4}–9.3×10^{-4})	0.0010 (8.4×10^{-4}–0.0011)	9.9×10^{-4} (8.2×10^{-4}–0.0012)	0.00110–0.00250

[a] Season sampled was unspecified.

[b] Trace minerals were not measured in any animals in the Calendar herd in early winter.

[c] Medians within a row followed by capital letters are significantly different from each other ($P\leq0.05$).

[d] NE = serum reference ranges not established for *Rangifer tarandus* sspp.

[e] Molybdenum levels were below detection limit for 25 caribou in Chinchaga, 10 in Maxhamish, 22 in Snake-Sahtaneh, and 13/14 caribou overall in the other herds.

TABLE 8. Serum trace minerals from adult female boreal caribou (*Rangifer tarandus caribou*) live-captured in late winter 2012–2013 in NE British Columbia, Canada, in this study and compared with reindeer and caribou (*R. tarandus* sspp.) from Puls (1994). Results are presented at the herd level only for herds that had a sample size of 10 or more animals.

Trace minerals	Median (interquartile range) (µg/mg)			Range[a]
	Calendar (n=17)	Snake-Sahtaneh (n=21)	All seven herds (n=48)	Reindeer and caribou (n=100)
Cobalt	4.7×10^{-4} (3.9×10^{-4}–5.3×10^{-4}) A[b]	5.9×10^{-4} (5.0×10^{-4}–7.6×10^{-4}) B	5.2×10^{-4} (4.6×10^{-4}–6.8×10^{-4})	NE[c]
Copper	4.0×10^{-4} (3.2×10^{-4}–4.6×10^{-4})	4.2×10^{-4} (3.6×10^{-4}–4.7×10^{-4})	4.0×10^{-4} (3.5×10^{-4}–4.6×10^{-4})	7.0×10^{-4}–0.0018
Iron	0.0077 (0.0053–0.012) A	0.0041 (0.0033–0.0061) B	0.0055 (0.0038–0.0082)	NE
Manganese	5.9×10^{-6} (4.9×10^{-6}–1.1×10^{-5}) A	4.6×10-6 (4.3×10^{-6}–6.2×10^{-6}) B	4.9×10^{-6} (4.3×10^{-6}–6.5×10^{-6})	NE
Molybdenum[d]	BDL	1.0×10^{-6} (1.0×10^{-6}–1.3×10^{-6})	1.0×10^{-6} (1.0×10^{-6}–1.3×10^{-6})	NE
Selenium	5.0×10^{-5} (4.7×10^{-5}–5.3×10^{-5})	5.0×10^{-5} (4.6×10^{-5}–5.1×10^{-5})	5.0×10^{-5} (4.7×10^{-5}–5.3×10^{-5})	5.0×10^{-5}–1.4×10^{-4}
Zinc	0.0013 (0.0011–0.0017)	0.0013 (0.0010–0.0021)	0.0013 (0.0011–0.0018)	0.00110–0.00250

[a] Season sampled was unspecified.

[b] Medians within a row followed by capital letters are significantly different from each other ($P \leq 0.05$).

[c] NE = serum reference ranges not established for *R. tarandus* sspp.

[d] Molybdenum levels were below detection limit (BDL) for 17 caribou each in the Calendar and Snake-Sahtaneh herds and in 10/10 caribou overall from the other herds.

S3). Molybdenum levels were not analyzed by herd because results from 85% of the samples tested were below the detection limit of the test (Tables 7 and 8). We considered there to be no significant differences by herd for selenium in early winter because the post hoc tests were insignificant despite the overall model being significant (P=0.049; see Supplementary Material Table S3). Hair cortisol concentrations did not differ significantly by herd and were within range of previously reported data for 48 free-ranging barren-ground caribou (*Rangifer tarandus groenlandicus*) in Greenland (Table 6; see Supplementary Material Table S3).

DISCUSSION

Our results on the health of boreal caribou expand on those by Johnson et al. (2010) and contribute to the broader literature on *Rangifer* health. Key findings include substantial hair loss, trace mineral deficiencies, and evidence of exposure to *E. rhusiopathiae*, an emerging pathogen in several ungulate species in North America (Kutz et al. 2015; Forde et al. 2016).

We observed a high occurrence of hair loss in all herds. On the basis of recovery of ticks from these animals, we attribute the hair loss primarily to irritation and excessive rubbing from winter tick infestations, as reported in moose (*Alces alces)* and captive *Rangifer* elsewhere (Welch et al. 1990; Samuel 1991). Severe hair loss might have been observed more commonly in late compared with early winter because caribou may have a delayed sensory response to adult ticks, which has been described in moose (Mooring and Samuel 1998). Throughout North America, moose are susceptible to late winter mortality from severe winter tick infestations (Samuel 2004). It is likely that winter tick infestations and associated hair loss could have similar energetic costs and effects on survival for BC boreal caribou. Winter ticks have been reported on boreal caribou in Alberta and the NT previously, but prevalence was extremely low, and hair loss was not reported in any of the animals observed (Welch et al. 1990; Kutz et al. 2009). Winter tick and associated hair loss has increased in incidence in captured BC boreal caribou within the last 15 years (Culling and Cichowski 2017). Moose are the primary host species of winter ticks in much of Canada (Samuel 2004). Winter tick populations may have increased in BC boreal caribou habitat from climate change and increases in moose occupying boreal caribou herd ranges (Schwantje et al. 2014).

Exposure to *E. rhusiopathiae* was detected in all herds. This bacterium is an opportunistic and generalist bacterium and has been reported as a cause of mortality in free-ranging moose and white-tailed deer (*Odocoileus virginianus*) in North America (Bruner et al. 1984; Campbell et al. 1994). It has also been associated with large-scale mortality events in free-ranging muskoxen (*Ovibus moschatus*) in the Canadian Arctic (Kutz et al. 2015) and acute mortalities of caribou and moose in BC and Alberta (Forde et al. 2016). *Erysipelothrix rhusiopathiae* was cultured from the carcasses (tissue, bone marrow, and blood) of seven of 16 boreal caribou in the study site that died during 2013–2014 (Forde et al. 2016). The individual and population consequences of this bacterium for caribou and other free-ranging ungulates are unknown and are the subject of ongoing research.

Trace mineral deficiencies can be underlying causes of wildlife population morbidity, suboptimal performance, or declines but are often overlooked (Flueck et al. 2012). Although trace mineral levels are ideally measured from liver and kidney, this requires postmortem or biopsy sampling, which was not always possible in this study. Serum trace mineral analyses are commonly used for domestic livestock (Herdt and Hoff 2011); however, reference ranges are rare to nonexistent for most wildlife species, including *Rangifer*. Nevertheless, on the basis of limited trace mineral data available for *Rangifer* (Puls 1994), we suspected deficiencies in all herds for copper and selenium but not for zinc. The effects of these deficiencies on caribou are unclear, but deficiencies in copper and selenium have been associated with clinical

disease in adults and neonates and with subclinical poor health and productivity in other ruminants (Flynn et al. 1977; Flueck et al. 2012).

Antlerless females were found in all herds except Chinchaga. Female woodland caribou typically shed their antlers soon or after parturition (Bergerud et al. 1984). However, in some populations of *Rangifer*, nonpregnant females tend to shed their antlers in early winter (Bergerud 1976). Pregnancy was not associated with the winter shedding of antlers in this study because all 10 of the antlerless females tested pregnant at the time of capture. Both genetics and nutrition can affect the presence or absence of antlers in female *Rangifer* (Reimers 1993). There is a tendency for herds in poor habitats to have a high frequency of antlerless females (Reimers 1993). It is unknown whether the absence of antlers in female boreal caribou in BC is genetic or indicative of inadequate nutrition and poor forage quality.

Seropositivity to a ruminant alphaherpesvirus that was serologically related to bovine herpesvirus 1 was high and common across all herds. A cervid herpesvirus (CvHV2) endemic to populations of reindeer in Norway (Tryland et al. 2009) has been identified in caribou in North America (das Neves et al. 2010), and we suspect the virus circulating in boreal caribou to be the same or similar to CvHV2. Cervid herpesvirus can be activated from latency by stress (Tryland et al. 2009) and has been associated with ocular infections (Tryland et al. 2017; Romano et al. 2018), respiratory disease, secondary bacterial infections, abortions, and neonatal morbidity and mortality in reindeer in Norway (das Neves et al. 2010). We did not observe any such acute clinical disease in the sampled animals.

Pestiviruses such as BVDV-1, BVDV-2, and border disease virus (BDV) can cause respiratory and reproductive disease, as well as mortality in ruminants (Vilček and Nettleton 2006). Seroprevalence to pestivirus was low in the sampled caribou. However, antigenic variation between pestiviruses of *Rangifer* and domestic cattle (*Bos taurus*) may reduce the sensitivity of the test (Larska 2015) and might explain why several borderline serology results were obtained and why the sample seropositive for BVDV tested negative for BVDV using the virus neutralization test.

The pestivirus circulating in reindeer is likely BDV-like, specific and endemic to their populations, and not yet described (Kautto et al. 2012). Antibodies to pestivirus using serologic tests based on BVDV-1 strains isolated from cattle have been found in caribou subspecies in North America and Europe (Larska 2015), but there are no reports on the isolation of pestivirus from wild or semidomesticated *Rangifer*. A pestivirus, designated V60, was isolated from a Eurasian tundra reindeer (*Rangifer tarandus tarandus*) with fatal diarrhea and anorexia in a German zoo (Becher et al. 1999), and phylogeny indicated that pestivirus V60 was most closely related to BVDV-2 (Avalos-Ramirez et al. 2001; Becher et al. 2003). Reindeer experimentally infected with BVDV-1 developed clinical illness and developed laminitis (Morton et al. 1990).

We observed a high overall seroprevalence to the protozoan *Besnoitia* spp. parasites across all herds. Although the serologic tests we used could not distinguish between *Besnoitia tarandi* and *Besnoitia besnoiti* because of cross-reactivity (Gutiérrez-Expósito et al. 2012), we presume the species to be *B. tarandi* because this species is common in barren-ground caribou throughout most of their range (Kutz et al. 2012), and *B. tarandi* was reported in woodland caribou in BC in the 1980s (Lewis 1989). In captive and free-ranging *Rangifer*, *B. tarandi* has been associated with reduced mobility, poor body condition, morbidity, mortality, reproductive disease, including male infertility, and several cases of severe debilitating disease (Wobeser 1976; Glover et al. 1990; Ducrocq 2010). In free-ranging caribou, significant disease outbreaks from *B. tarandi* have only been reported in barren-ground caribou in Quebec and Labrador (Kutz et al. 2012).

Exposure to the apicomplexan protozoa *N. caninum* was detected in two herds. Although its effect in *Rangifer* is not well understood, *N. caninum* was the suspected cause of a large

outbreak of mummified fetuses in a herd of captive reindeer (Kutz et al. 2012). In cattle, *N. caninum* can also be passed to the fetus in utero and increase the risk of abortion in the surviving offspring (Thurmond and Hietala 1997). Although wild and domestic canids are definitive hosts for this parasite (McAllister et al. 1998; Dubey and Schares 2011), white-tailed deer are one of the most important intermediate hosts in the United States (Dubey et al. 2017). These deer are expanding their range into areas of NE BC (Culling and Cichowski 2017) and may serve as amplification hosts for *N. caninum* with implications for reproduction of boreal caribou. *Toxoplasma gondii,* a related apicomplexan parasite with similar effects on reproduction in ungulates but with a felid definitive host (Dubey and Odening 2001), was not detected. This was somewhat surprising given that it is commonly found in other caribou subspecies across North America (Kutz et al. 2012).

The diversity, prevalence, and intensity of gastrointestinal helminth eggs and protozoal oocysts was low and consistent with previous studies on barren-ground caribou (Hoar et al. 2009; Kutz et al. 2012; Steele 2013). Our results likely underestimated diversity and abundance. For example, some parasites (e.g., Nematodirines and *Eimeria* spp.) are more common in young animals, and the detection of *Moniezia* eggs is dependent on whether the tapeworm's proglottids (segments) are shed at the time of sampling (Kutz et al. 2012). In addition, prevalence and intensity of some gastrointestinal parasites (e.g., *Ostertagia gruehneri*) varies seasonally (Irvine et al. 2000), and each individual was only sampled once. Finally, the eggs of many species that produce "strongyle-type" eggs are adversely affected by freezing of samples before analysis (Foreyt 1986; de Bruyn 2010).

The only protostrongylid we detected in the feces was *Parelaphostrongylus andersoni*. This muscle nematode is widespread in woodland and barren-ground caribou from central, north-central, and eastern Canada (Kutz et al. 2007; Verocai 2015). Although infection with this parasite can cause significant muscular and pulmonary disease in caribou, little is known about its ecology and effects on caribou populations (Kutz et al. 2012). *Varestrongylus eleguneniensis* may have been present but not detected in this study because PCR was only run on DSL from six samples, and morphologic keys differentiating these larvae (Kafle et al. 2017) were not available at the time the samples were analyzed. Verocai (2015) detected *V. eleguneniensis* in most boreal caribou populations across North America from 2003 to 2010, including in five of 14 caribou from the Chinchaga herd, but none of the caribou from the Calendar (n=17), Maxhamish (n=3), or Snake-Sahtaneh (n=12) herds.

Some of the caribou sampled in BC had potassium or albumin:globulin ratios above the ranges of those reported by Johnson et al. (2010) in the NT. It is possible that the high potassium levels of the caribou in NE BC were falsely high. Pseudohyperkalemia in mammals, including humans and domestic horses, pigs, and cattle, can occur with improper handling of samples, delays in centrifugation, hemolysis, or cold temperatures from transport in winter (Carlson 1997; Asirvatham et al. 2013). When hyperkalemia in a population of 60 free-ranging white-tailed deer was investigated, renal excretion, seasonality, poor forage quality, and method of capture were all identified as possible contributing factors, and a delay in processing the samples was ruled out (Stringer et al. 2011). In contrast to the population of deer observed by Stringer et al. (2011), hyperkalemia was not detected in all of the caribou in any of the BC herds. We suspect that sample processing and handling in the field played a role in the hyperkalemia of the caribou in this study because 14 of the 20 samples with high potassium levels were collected from the Snake-Sahtaneh and Chinchaga herds on five capture dates for which all of the samples collected yielded high potassium results. The albumin:globulin ratio differences might not be biologically significant because the globulin and total protein levels and 94% of the albumin levels of caribou from NE BC were within range of those from the NT. Although capture stress may have affected some serum

biochemistry values (e.g., potassium, total protein, albumin, sodium, and chloride; DeLiberto et al. 1989; Marco and Lavin 1999), the effects are likely consistent with those from the NT because the same capture crew and techniques were used.

Acute phase proteins, such as SAA and haptoglobin, can increase during acute and chronic bacterial or viral infections (Orro et al. 2004; Ulutas et al. 2011; Sharifiyazdia et al. 2012) and are commonly used as biomarkers of inflammatory disease in clinical veterinary medicine (Eckersall and Bell 2010). Serum amyloid A levels in the Calendar herd were uniformly high and similar to those of reindeer exposed to endotoxin in a challenge trial conducted by Orro et al. (2004), which suggests an inflammatory process. In contrast, haptoglobin ranges in all sampled herds were below the levels observed by Orro et al. (2004) in both treatment and control groups.

Glucocorticoid measurements such as hair cortisol concentrations are increasingly being used as noninvasive physiologic indices of chronic stress (Ellis et al. 2012) and the health and fitness of individuals and populations (Macbeth and Kutz 2018). Hair cortisol concentrations in this study were within range of those determined using the same assays for free-ranging caribou in Greenland and Alaska (Macbeth 2013) and captive reindeer in Canada (Carlsson et al. 2016). Hair cortisol concentration in caribou captured in winter is hypothesized to reflect stress that occurred in the preceding spring through late summer during the period of active hair growth (Macbeth 2013). However, hair cortisol concentration has not been validated as an indicator of long-term stress in wildlife (Cattet et al. 2014). In grizzly bears (*Ursus arctos horribilis*), hair cortisol concentration was associated with long-term stress and acute stressors such as capture and handling (Cattet et al. 2014). In muskoxen, data suggest that hair cortisol concentration might be influenced by acute stressors, as well (Di Francesco et al. 2017).

Stress, trace minerals, infectious and noninfectious diseases, and contaminants can play an important role in wildlife population dynamics (Deem et al. 2001; Carlsson et al. 2018; Macbeth and Kutz 2018). Monitoring such health indices in a standardized manner from live and dead animals should be part of caribou conservation and management plans (Kutz et al. 2012; Macbeth and Kutz 2018) and wildlife collaring and monitoring programs. We established a fairly comprehensive set of health indicators across seven boreal caribou herds, yet we also identified several challenges to both measuring these indices and interpretation of results. Similar challenges have been discussed by Carlsson et al. (2018) and include: 1) few serologic tests previously validated for caribou; 2) the lack of reference intervals for several biochemical values, acute phase proteins, and trace minerals; 3) the need to extrapolate from domestic species to understand the potential pathophysiology in caribou; and 4) small effective sample sizes. Despite these limitations, our results provided a comparative point to which these same herds could be assessed and other populations evaluated through time.

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SUPPLEMENTARY MATERIAL

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LITERATURE CITED

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