CANADIAN WILDLIFE HEALTH COOPERATIVE
RÉSEAU CANADIEN POUR LA SANTÉ DE LA FAUNE

RISK ANALYSIS OF PNEUMONIA-RELATED PATHOGEN TRANSMISSION FROM DOMESTIC SMALL RUMINANTS TO WILD THINHORN SHEEP IN YUKON AND NORTHERN BC

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1. EXECUTIVE SUMMARY

Purpose of risk assessment: The presence of domestic small ruminants in northern Canada has raised concerns about the potential for pathogen transmission and disease outbreaks to occur in presumably naïve thinhorn sheep (Stone's and Dall's sheep). The purpose of this report is to assess the risk of pneumonia associated with domestic small ruminants to thinhorn sheep in Yukon and northern British Columbia. The goal was to summarize and assess available information to identify pathogens of concern for wild sheep in Yukon and northern British Columbia, determine the consequences and likelihood of pathogen transmission from domestic to wild sheep, estimate the risk of disease outbreaks, identify mitigation options and knowledge gaps, and make recommendations for future management and research.

Main conclusions: The exact nature of the risk of pneumonia of thinhorn sheep acquired from domestic sheep cannot be determined for Yukon and northern British Columbia due to limits in available information. However, there is sufficient evidence and opinion to conclude that the unquantified risk to thinhorn sheep from pneumonia associated with domestic small ruminant exposure warrants a proactive management response in Yukon and northern British Columbia. Preventing exposure of thinhorn sheep to domestic sheep is a reasonable precautionary management response because the apparent low risk of exposure is countered by the likely high impacts of transmission of pathogens from domestic small ruminants to thinhorn sheep. Economic implications of management policies cannot be estimated due to information gaps.

There is widespread scientific evidence and professional opinion that domestic sheep are a significant risk factor for pneumonia in bighorn sheep and subsequently an impediment to species conservation and recovery. There is no evidence to reject the conclusion that it is highly likely that thinhorn sheep are susceptible to the domestic sheep pathogens that cause pneumonia in individual animals and subsequent population limiting effects. The magnitude of possible effects and lack of ability to mitigate the population limiting effects in wild sheep makes this a risk that requires proactive management attention.

There is a range of pathogens that have been associated with wild sheep morbidity and mortality, and with herd die-offs in bighorn sheep in other jurisdictions. Pneumonia in wild sheep is multifactorial where interactions between host, agent, and environmental factors create a web of causation that is very challenging to separate into its various components. It has been demonstrated that pneumonia outbreaks in bighorn sheep result from a mix of exposure to infectious microbes with a variety of additional factors such as poor nutrition, degraded or reduced habitat, human-caused stressors, extreme weather conditions, parasite loads, and the presence of domestic livestock. Variation in the interactions of these factors make it difficult to make simple conclusions on a single cause of wild sheep pneumonia as the relative importance of these factors vary from case-to-case. The bulk of available evidence indicate that interactions between wild sheep and domestic sheep increase the probability of death and reduced lamb survival in wild sheep populations, primarily because of respiratory disease.

As a result of strong supporting evidence, segregation of wild sheep from domestic sheep and goats is a cornerstone of preventing pneumonia in bighorn sheep, but specific distances of separation cannot be prescribed consistently across all circumstances. The practice of sheep grazing in Yukon and northern BC is currently confined to a very small part of the territory thereby limiting the effects of a policy of separation to a small geographic area.

Recommendations: Uncertainty affecting risk estimation specific to Yukon and northern British Columbia can be reduced by acquiring information to; 1) characterize the likelihood of domestic small ruminant and thinhorn sheep co-mingling and/or range overlaps, to assess exposure risks; 2) undertake a cost: benefit analysis of management implications to improve assessment of the magnitude of risk; 3) develop Yukon-specific information on the nature, distribution, and prevalence of potential pneumonia-causing microorganisms and; 4) develop Yukon-specific information regarding the nature, distribution, and prevalence of non-microbiological risk factors for pneumonia in wild sheep. Risk reduction actions can include; 1) establishing domestic small ruminant grazing policies that prescribe locations, animal numbers/densities, and health expectations of domestic animal use of land important to wildlife; 2) developing a unified program of risk management in British Columbia, Yukon, Alberta, and Alaska; 3) identifying areas with the highest probability of domestic ruminant-thinhorn sheep contact and establishing protocols to monitor interactions between domestic ruminants and thinhorn sheep; 4) developing domestic ruminant health best management plans and establishing minimum standards of health required before allowing domestic small ruminants to graze in important wildlife habitats and; 5) supporting adaptive management through a regional thinhorn sheep risk management working group. Collaboration between the governments of British Columbia, Alberta, Northwest Territories, and Alaska to identify regional research needs and to share information is encouraged.

2. REASON FOR REQUEST

The presence of domestic small ruminants in the north has raised concerns about the potential for pathogen transmission and disease outbreaks to occur in presumably naïve thinhorn sheep (Stone's and Dall's sheep) herds in Yukon and northern British Columbia. Of particular concern is the risk of pneumonia-causing pathogen transmission from domestic sheep to wild thinhorn sheep in Yukon and northern British Columbia and the risk of pneumonia outbreaks in wild sheep herds from contact with domestic small ruminants.

The purpose of this project is to use available scientific data and other resources, including interviews with specialists to:

1. Identify the pathogens of concern for pneumonia outbreaks in wild thinhorn sheep herds;
2. Provide a qualitative assessment of the risk of pneumonia-related pathogen transmission from domestic ruminants to wild thinhorn sheep in Yukon and northern BC; the potential impact of transmission on wild sheep health and; the risk of pneumonia outbreaks occurring in wild thinhorn sheep;
3. Identify potential consequences of pathogen transmission and pneumonia outbreaks in wild thinhorn sheep including ecological, economic, and social consequences;
4. Assess the gaps in available knowledge on the risks of pneumonia outbreaks in wild thinhorn sheep;
5. Present potential future research questions that would improve our understanding of the risks and consequences of pneumonia outbreaks in wild thinhorn sheep and;
6. Identify mitigation measures that could minimize or eliminate the risk of pathogen transmission and disease outbreaks in wild sheep in Yukon and northern BC.

3. BACKGROUND

The purpose of this background section is to provide the reader with context that can help to assess and interpret the risk analysis that follows for thinhorn sheep in Yukon and northern British Columbia (BC). It is composed of two parts: (1) an overview of thinhorn sheep and the domestic sheep industry in Yukon and (2) a summary of the science and past risk assessments on the association of pneumonia-causing pathogen transmission between domestic small ruminants and wild sheep. The latter information deals largely with bighorn sheep. It is not our purpose to replicate past risk assessments for bighorn sheep, but rather to highlight and summarize key findings that are relevant to the thinhorn sheep context in Yukon and northern British Columbia.

3.1 THINHORN SHEEP DISTRIBUTION, ABUNDANCE, AND ECOLOGY

Thinhorn sheep include two sub-species or races; the white Dall's sheep (*Ovis dalli dalli*) and black Stone's sheep (*O. dalli stonei*). They are called thinhorn because the horns of the rams are more slender and sharply pointed than those of the bighorn sheep (*O. canadensis*) found in southern BC, Alberta, and the western United States. The two subspecies interbreed where their ranges overlap producing offspring with pelt colourations varying from pure white to shades of grey to brownish black (Demarchi & Hartwig 2004).

Thinhorn sheep are found in northern BC, in the Mackenzie and Richardson mountains of the Northwest Territories (NWT) and throughout much of Yukon and interior Alaska (Demarchi & Hartwig 2004) (see Figure 1). Yukon has more wild sheep than any other region in Canada, all of which are thinhorn sheep. The International Union for the Conservation of Nature (IUCN) website relied on references from the mid-1980's and reported that the total population of thinhorn sheep in Canada was approximately 41,500 animals; 27,000 Dall's sheep (with 19,000 in Yukon), 7,500 in NWT, and 500 in BC), and 14,500 Stone's sheep (with 3,000 inYukon, and 11,500 in BC). The total United States (U.S.) population was estimated to be between 70,000 and 75,000 animals. More recent population estimates for Yukon suggest there are 22,000 thinhorn sheep in the territory, with six times more Dall's sheep than Stone's sheep (Government of Yukon 2014). In 2012, Kuzyk et al. reported the population abundance of thinhorn sheep in BC had been relatively stable since 1987, ranging between 9,900 and 15,000 animals. The population of Dall's sheep in BC was reported as approximately 400-600 animals in 2003 (Schwantje & Stephen 2003). Much of the BC population is found within Tatshenshini-Alsek Provincial Park in the northwest corner of the province. Most of the world's population of Stone's sheep are found in northern British Columbia (Province of BC 2000).

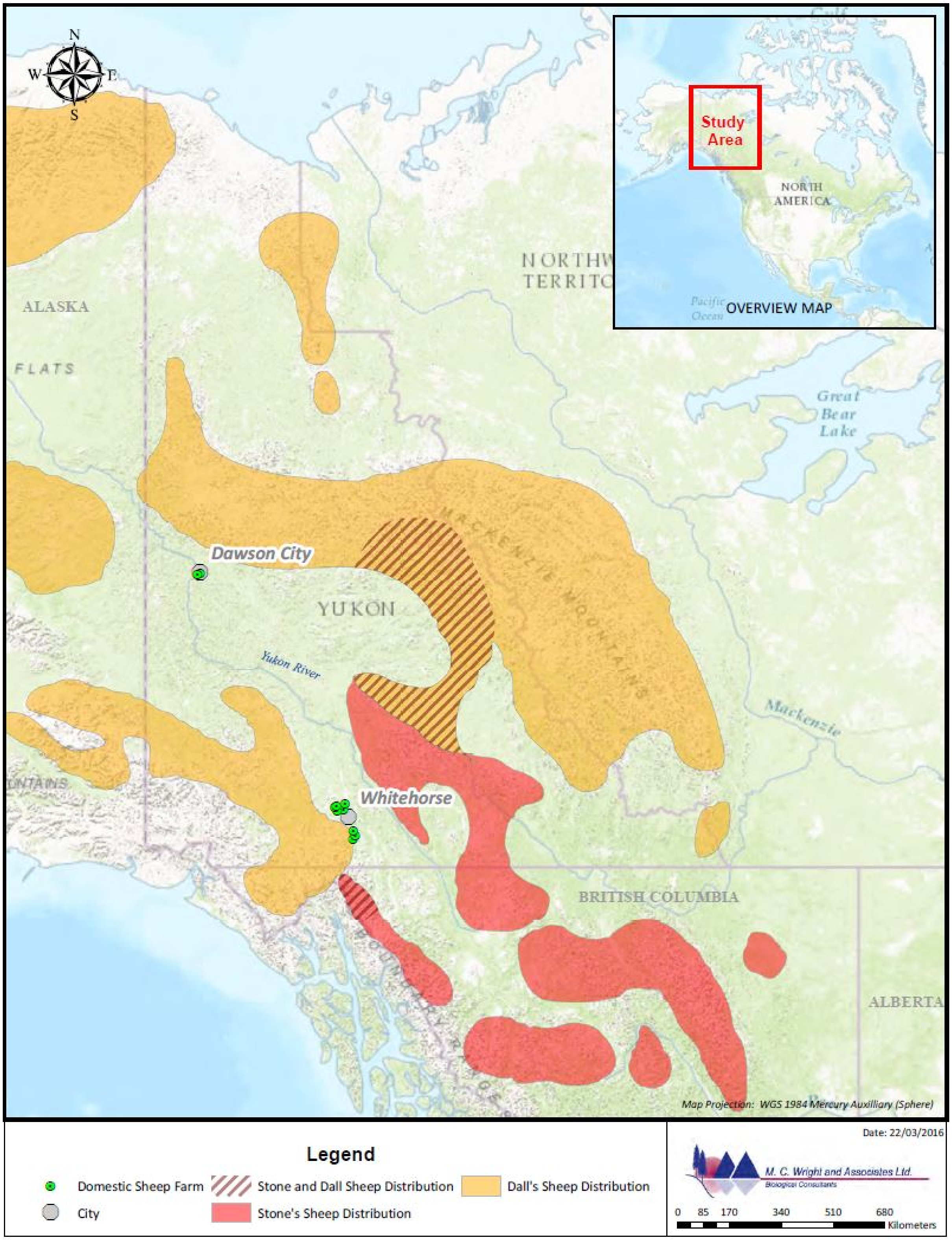

Figure 1: Map showing the distribution of Dall's and Stone's sheep and known locations of Yukon farms believed to be raising domestic sheep.

In Yukon, wild sheep live on mountain peaks from the territory's southern border to near the Arctic coast. Thinhorn sheep inhabit open mountain slopes in the sub-alpine and alpine zones (Demarchi & Hartwig 2004). The highest concentration of Stone's sheep are found on lower mountain areas to the northeast of high-elevation mountains (Demarchi & Hartwig 2004). In the northern part of their range, Dall's sheep prefer habitats with relatively shallow and soft snow, with a cold dry climate (Demarchi & Hartwig 2004). Sheep inhabiting the southern part of the range prefer a winter range with more precipitation and warmer temperatures with occasional thawing (Demarchi & Hartwig 2004). Yukon thinhorn sheep spend the summer grazing in alpine meadows eating grasses, sedges, and broad-leaved forbs. Winter range can be nearby or many kilometres away. The sheep use the same migration routes between summer and winter ranges generation after generation. They winter on south-facing slopes at fairly low elevations for up to nine months. Dall's sheep usually inhabit open grasslands above treeline while Stone's sheep use treed and shrubby areas (Government of Yukon 2014). Thinhorn sheep are a herd animal, uncommonly seen alone, although they may become widely scattered during summer (Bunnell 2005). These animals move seasonally to find forage as well as undertake long distance movement to find salt licks. Thinhorn sheep are gregarious and have a well-developed social system. Rams and ewes are rarely found in the same groups outside of the mating season. Rams may occupy as many as six seasonal home ranges including prerutting range, rutting range, midwinter range, late winter and spring range, and summer range (Geist 1971 in Bowyer and Leslie 1992). Ewes have notably small numbers of ranges including winter, spring, lambing, and summer ranges (Geist 1971 in Bowyer and Leslie 1992). The use of home range is highly conserved between generations, where young are said to "inherit" home ranges from older individuals (Geist 1971 in Bowyer and Leslie 1992). It is noted in Geist (1971) that midwinter ranges were the smallest (minimum size of 0.8 km diameter) and spring and autumn ranges were largest, approximately 6 kilometres in diameter.

Thinhorn sheep mature slowly and have low reproductive rates. Ewes normally produce only one lamb per year. Overharvesting, disturbance, and forage availability are considered the major threats to the population although little is known of the health or disease status of thinhorn sheep (Schwantje & Stephen 2003). Thinhorn sheep appear to be as sensitive to similar pressures as bighorn sheep and perhaps more so, since human access is much more recent (Jenkins et al. 2000; Kutz et al. 2001). During the Gold Rush, sheep populations were hunted almost to extinction in order to feed new settlements. Road crews building the Alaska highway took a heavy toll on sheep in south-western Yukon (Government of Yukon, no date).

3.2 What is at risk?

First Nations' value

First Nations have traditionally hunted Dall's sheep for their meat, fleece for blankets and clothing and horns for cookware (Government of Yukon website http://www.env.gov.yk.ca/animals-habitat/mammals/sheep.php). Canada has Constitutional obligations to protect fish and wildlife to ensure Aboriginal communities have access to adequate food, including the right to feed themselves and to participate in decisions about their food system. Despite profound social and economic change, Aboriginal peoples throughout northern Canada maintain a lasting connection with the environment through hunting (Natcher 2009). The traditional economy based on subsistence hunting and food sharing is part of Yukon's economy. We found no estimates of its dollar value of traditional uses of sheep but found comments on its cultural value. Thinhorn sheep continue to bring value to a number of First Nations communities and individuals have been involved in guide outfitting and tourism (Paquet & Demarchi 1999).

HUNTING

Wild sheep are important for subsistence and resident hunters in the Yukon and for a non-resident outfitted hunting industry. Thinhorn sheep are one of the most prized trophy animals in North America and contribute significantly to the big game outfitting industry in the region (Government of Yukon, no date).

Sheep hunting in the Yukon is subject to harvest regulations. Hunters must possess a big game (sheep) seal and a hunting permit. Hunting occurs through an open general season in Game Management Subzones where harvest is permitted (Jex et al. 2016). From 2011 to 2015, 1111 sheep were harvested (average 222/year) from 159 Game Management Subzones (GMS) in the Yukon (Table 1). The largest average number of sheep were harvested from Game Management Zone (GMZ) 5 (11.38 animals/area) followed by GMZ 7 (10.6 animals/area). Zone 5 includes the area to the north east of Whitehorse extending to the border with Alaska. Zone 7 is found immediately to the south of Whitehorse (Figure 2) and includes the largest number of documented sheep farms (See Figure 1). A total of 109 resident permits were used during this time. The remaining sheep were harvested under non-resident permits. Non-resident Canadians must be guided by a registered Yukon outfitter or guided by a Yukon resident holding a Special Guide License. Only "full curl" males are permitted to be harvested; females, young, and males with horns less than full curl are protected. Full curl males are approximately 8 years of age and older.

A voluntary resident hunter survey was compiled by Yukon Environment for the 2012 hunting season (Westfall 2013). No economic data were collected however, species-specific effort was targeted. It was found that the majority of respondents (54%) went on one sheep hunt in 2012. Of those who hunted sheep that year, 76% hunted in August, 36% hunted in September, and 19% hunted in October (Westfall 2013). Most hunting took place in Game Management Zones 5 and 7 and, 14% and 47% of respondents wanted to hunt in Zones 5 and 7, respectively. Sixty eight percent of the respondents were living in Whitehorse in November 2012 (Westfall 2013). Of the respondants, 49% of sheep hunters hunted for food purposes (Westfall 2013).

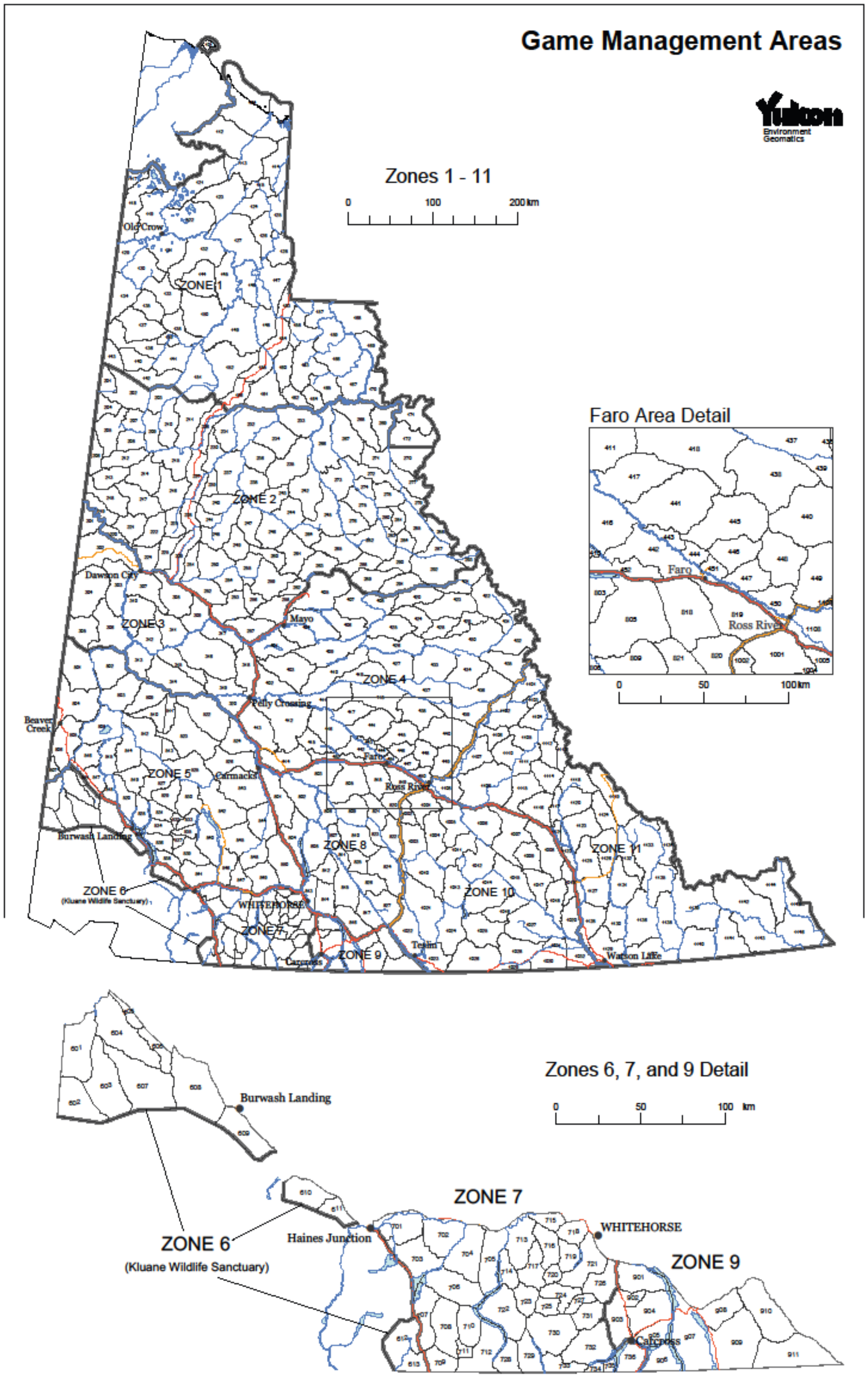

Figure 2: Map of Yukon Game Management Zones (source: http://www.env.gov.yk.ca/hunting-fishing-trapping/documents/GMA_Map.pdf)

Data were not available to calculate the total economic contribution of the thinhorn sheep hunt to Yukon's economy. The Yukon Outfitters Association is currently undertaking a project to determine the revenue generated through outfitter hunting activities (Rob Florkiewicz, Personal Communication). Annual revenues from the sale of seals over the past 10 years (2006-2015) have varied from $10,210 to $12,700 per year (Table 2). This does not include other licence and permitting costs and fees associated with the hunt, nor does it include revenue derived through guiding activities. Thinhorn sheep are an important component of guide outfitting in northern British Columbia. In 2000, what was then the Department of Renewable Resources of Yukon conducted a voluntary hunter survey (55% response rate). It was estimated that hunting (all species) generated $2.2 million in economic activity (approx $610/hunter) and that Yukoners spent 1639 days hunting sheep (16% of trips were successful).

It has been estimated that hunters spent more than $7 million dollars to hunt Alaskan Dall's sheep, contributing approximately $2.5 million to the state's economy in 1983, more recent data were not found (Alaska Chapter of the Wildlife Society 2005). With inflation, these figures may have doubled. It has been estimated that the net economic value for hunting mountain sheep in the Peace-Omineca region of BC in 1996 was $1,017,35 (Paquet & Demarchi 1999). Caution must be used when interpreating estimates of economic value of hunting in the north, particularly wild sheep hunting, due to limited surveys, outdated information, and limits to the methods used to estimate economic value. Data on the contributions of sheep to subsistence hunting were not found.

Table 1: Sheep harvest from 2011 to 2015 from Game Management Zones (GMS=Game Management Subzone) (Rob Florkiewicz, Government of Yukon. personal communication).

Game Management Zone	Total number sheep harvested	Number of GMS hunted	Average number of sheep harvested per sub-zone
2	317	53	5.98
4	105	22	4.77
5	330	29	11.38
6	4	3	1.33
7	266	25	10.64
8	36	11	3.27
9	6	2	3
10	44	12	3.67
11	3	2	1.50
Total	**1111**	**159**	

Table 2: Summary of revenue derived from seal sales from the wild sheep hunt in the Yukon (Rob Florkiewicz, Government of Yukon. personal communication).

Year	Resident (Non-Native)				Non-Resident		Total	
	total resident seals	minus hunters > 64	seals sold with revenue	revenue	seals sold	revenue	seals sold	revenue
2015	1044	141	903	$9,030	367	$3,670	1,270	$12,700
2014	982	137	845	$8,450	365	$3,650	1,210	$12,100
2013	927	131	796	$7,960	327	$3,270	1,123	$11,230
2012	916	115	801	$8,010	279	$2,790	1,080	$10,800
2011	872	118	754	$7,540	267	$2,670	1,021	$10,210
2010	890	113	777	$7,770	277	$2,770	1,054	$10,540
2009	892	102	790	$7,900	292	$2,920	1,082	$10,820
2008	887	89	798	$7,980	320	$3,200	1,118	$11,180
2007	830	82	748	$7,480	312	$3,120	1,060	$10,600
2006	768	68	700	$7,000	350	$3,500	1,050	$10,500
Revenue				**$79,120**		**$31,560**		**$110,680**

DOMESTIC SHEEP FARMING

Agriculture is a small industry in Yukon with less than two per cent of theTerritory being suitable for agricultural development (Government of Yukon 2013). Agriculture activity takes place largely south of 64.5° north latitude with most activity occuring in the Takhini Valley agricultural area, west of Whitehorse as well as near Dawson City, Watson Lake, and Mayo[1].

We were unable to determine the total number of domestic sheep or sheep farms currently in Yukon nor were there records available to map the precise locations of all farms and any grazing lands. The Agriculture Branch, Government of Yukon does not maintain a list of active sheep farms or numbers of head (Kevin Bowers, Government of Yukon, personal communication). Through a combination of sources including the current Yukon Agricultural Guide (http://www.yukonag.ca/guide/), Yukon Farm Products and Services Listings (2013), and internet searches we compiled a list of 11 farms which likely have sheep for either fleece, meat, or hides. We do not believe this is a comprehensive list. The Yukon Agriculture State of the Industry report

[1] http://www.gov.yk.ca/aboutyukon/industry.html

for 2002-2004 (2005) states that at that time there were between 75-100 sheep and 100-150 goats on Yukon farms. The Yukon Agriculture 2008-09 interim report produced by Government of Yukon, Department of Energy, Mines and Resources, Agriculture Branch and Agriculture and Agri-Food Canada reported seven sheep farms with 113 animals. The state of the industry report published in 2013 references the 2011 Statistics Canada General Census (which was voluntary) stating that four farms reported a total of 72 sheep and lambs.

A report on the State of the Yukon Food System (Kwantlen Polytechnic University 2015) determined that combined, bee/honey, rabbit, sheep, goat and elk production generated $34,945 or 6% of the total livestock industry in 2012. Further information in that report from two sheep farms established that these farms sold 450 lbs of meat (at $6/lb – total $2,700) in 2012. Estimates of the economic value of meat or wool sold from other farms could not be found. We found no document describing plans for growth or development of the Yukon sheep industry other than a mention of goat/sheep opportunities and constraints in the Multi-Year Development Plan for Yukon Agriculture and Agri-Food 2008-2012 (Serecon Management Consulting Inc. 2007). Here it is noted that there are opportunities to continue to grow farm gate sales of sheep and goat products for dairy, meat, and fibre.

The Government of Yukon grants grazing rights on designated areas of public land to eligible applicants (Yukon Government Agriculture Branch 2015). Applications for grazing rights are reviewed by the Agriculture Branch for conflicts with wildlife, among other criteria. Most grazing applications are subject to an assessment by the Yukon Environmental and Socio-economic Assessment Board except where no fencing is required as part of the grazing management plan, the application would instead undergo a review by the Agriculture Branch (Government of Yukon 2010). In 2009, 39 grazing agreements (all species) were in existence, covering 10,838 hectares (average 266ha/agreement) (Government of Yukon 2010). The Yukon Animal Health Program (Environment Yukon) notes that the Government of Yukon is committed to rejecting sheep grazing or agricultural land applications within a buffer zone around and above 1,000 meters elevation as a measure to protect thinhorn sheep (Government of Yukon 2015). However, there is uncertainty in the Yukon about the recommended buffer zone distance around thinhorn sheep populations (Kevin Bowers, Government of Yukon. personal communication). Environmental Farm Plan and Farm Stewardship Programs exist in Yukon with the intention of fostering stewardship of soil, air, biodiversity, and water in and around farm land. These appear to be voluntary and proprietary plans. Their use in sheep and goat agriculture could not be established. There are no documented plans by the Government of Yukon to expand sheep and goat agriculture in the Yukon (Kevin Bowers, Government of Yukon. personal communication).

3.3 WHY IS DOMESTIC SHEEP-ASSOCIATED PNEUNONIA A CONCERN?

WHAT ARE THE EFFECTS OF PNEUMONIA IN WILD SHEEP?

Pneumonia is a devastating disease of bighorn sheep (*Ovis canadensis*) in North America and can be population limiting (Besser et al. 2008; Cassirer & Sinclair 2007; Hobbs & Miller 1992; McCarty & Miller 1998; Miller 2001; Monello et al 2001). The Wild Sheep Working Group (WSWG) of the Western Association of Fish and Wildlife Agencies (WAFWA) "recognizes that the potential adverse effects of disease of bighorn sheep populations as the highest concern among all management challenges identified" (Brewer et al 2014).

Populations of bighorn sheep declined from historic levels of approximately two million in the 1800's (Queen et al 1994) to 7000 Rocky Mountain, California, and Desert bighorn sheep in North America (Garde et al 2005). The decline has been primarily attributed to the incursion of domestic cattle and sheep into bighorn sheep territory resulting in overgrazing and/or habitat loss and the introduction of diseases transmitted from domestic sheep and goats (Valdez & Krausman 1999).

Diseases have contributed to dies-offs and serious declines of bighorn sheep populations of western North America (Miller et al 2012) with many populations declining to less than 10% of historical size (WSWG 2012) (see Table 3). Declines in bighorn sheep populations associated with outbreaks of respiratory disease have coincided with livestock grazing on ranges occupied by bighorn sheep (CAST 2008; Grinnell 1928; Honess & Frost 1942; Ryder et al 2014; Schilinger 1937; Warren 1910, WSWG 2012).

Pneumonia in wild sheep can result in all-age morbidity and mortality and is typically followed by extended periods of poor lamb recruitment and population declines (Brewer et al 2014). Chronic, although sporadic, pneumonia-caused mortality in adults and lambs can also have important effects on the dynamics of bighorn sheep populations (Cassirer & Sinclair 2007). Studies of outbreaks show that population effects can come from four different age classes (Cassirer et al 2013); 1) all-age 2) lamb-only 3) secondary all-age and 4) adult-only. Each of these types of outbreaks by themselves have different levels of effects on population abundance. The cumulative effects however are often devastating for population recovery. For example, years in which recutiment was low due to high lamb mortality posed a significant obstacle to population recovery due to chronically infected ewes (Cassirer et al 2013).

Table 3: Bighorn sheep pneumonia die-offs, winter 2009-2010 in Montana, Nevada, Washington, Utah, and Wyoming (Reproduced from WAFWA June 22, 2010 report).

Location	Estimated population (pre-die off)	# culled	# known additional mortalities	Estimated mortality (%)	Estimated mortalities (#)	Association with domestic sheep or goats pre die off
East Fork Bitterroot, MT	200-220	80	NA	50	100	Known
Bonner/W Riverside, MT	160-180	99	4	68	110	Known
Lower Rock Creek, MT	200	18	NA	43	87	Possible
East Humboldt Range, NV	160-180	1	113	80	140	Likely
Ruby Mountains, NV	160	1	36	65	100	Possible
Yakima River Canyon, WA	280	69	42	33	99	Possible
N slope Uinta Mountains, UT	50-70	51	0	95	50	Unknown
Gros Ventre River, WY	50-60	2	0	5	2	Unknown
Total	**1600-1680**	**360**	**195**		**888**	

Table 4: Bacterial pneumonia related die-offs in bighorn sheep in Canada (BC=British Columbia, AB=Alberta, UBC=University of British Columbia) (reproduced from Garde et al 2005).

Year	Location	Proposed cause	Outcome
1999-2000	Okanagan Valley, BC	Bacterial pneumonia, mixed organisms, domestic contact	75% dead
1998	Elk Valley, east Kootenay, BC	Bacterial pneumonia, *P. multocida*	Low mortality, no progresion

Year	Location	Proposed cause	Outcome
1988	Captive herd, AB	Pneumonia after vaccine trial	100% mortality
1985-86	Sheep River, AB	*Mannheimia haemolytica* type A	62-65 animals reported dead
1981-1983	East Kootenay, BC	Multiple organisms, lungworm	Approximately 65% reduction in multiple herds
1978	Sheep River Sanctuary, AB	Pasteurella/verminous pneumonia	10% mortality
1970s	UBC captive herd	Pneumonia	100% mortality
1964-1966	East Kootenay, BC	Bacterial and verminous pneumonia, domestic contact	Significant mortality in multiple herds
1920s	East Kootenay, BC	Bacterial and verminous pneumonia, domestic contact	Significant mortality in multiple herds

DO WILD SHEEP ACQUIRE PNEUMONIA FROM DOMESTIC SHEEP?

The bulk of available evidence from empirical studies and field observations indicates that interactions between wild sheep and domestic sheep increase the probability of death and reduce lamb survival in wild sheep populations, primarily because of respiratory disease (CAST 2008). Domestic sheep and goats commonly carry the micro-organisms that cause pneumonia. It is widely believed that these disease causing organisms can be transmitted to bighorn sheep upon contact with, or proximity to domestic sheep or goats, resulting pneumonia outbreaks that are frequently fatal to bighorn sheep within a few weeks (CAST 2008).

A 2006 risk assessment conducted by the United States Department of Agriculture regarding disease transmission between domestic and wild sheep in the Payette National Forest concluded that the available scientific literature supports the following statements (USDA 2006):

1) Numerous examples of bighorn die-offs due to disease have been documented;
2) Bighorn die-offs were documented as early as the mid 1800s and have been documented in every state in the western U.S.;
3) Bighorn die-offs typically follow known or suspected contact with domestic sheep;
4) Under experimental conditions, clinically healthy bighorn sheep have developed pneumonia and died within days to weeks following contact with clinically healthy domestic sheep;
5) A variety of diseases and pathogens have been implicated in die-offs; and

6) It is consensus among wildlife biologists and veterinarians experienced in bighorn sheep management that domestic sheep and bighorn sheep must be kept separated in order to maintain healthy bighorn populations.

A 2011 review of evidence linking domestic sheep, wild sheep, and respiratory disease (Wehausen et al 2011) concluded the following:

> *"1) experiments have repeatedly corroborated the hypothesis that bighorn sheep have a high probability of contracting fatal pneumonia following contact with domestic sheep;*
> *2) low disease and mortality rates in numerous co-pasturing pen studies involving bighorn sheep and animals other than domestic sheep do not support the alternative explanation that the results of the co-pasturing studies involving domestic sheep were an artifact of captivity; and;*
> *3) the identification of which organism(s) cause pneumonia in bighorn sheep following contact with domestic sheep remains unresolved, possibly because of disease complexity (multiple pathogens) and limitations of research tools applied*."

The risk of wild sheep developing pneumonia after contact with domestic sheep varies from location-to-location and situation-to-situation because the risk is affected by multiple, interacting factors including: interactions of sufficient duration and proximity to transmit one or more pathogens; amounts of pathogen shedding by domestic sheep; the ability to transmit an infectious dose to one or more wild sheep; the survival of newly infected wild sheep; further shedding and secondary transmission between wild sheep; and other agent, seasonal or environmental factors (Miller et al 2008).

3.4 WHAT CAUSES WILD SHEEP PNEUMONIA?

Wild sheep pneumonia is a multifactorial disease, meaning that multiple factors are usually responsible for the development of clinical disease. Pneumonia outbreaks in bighorn sheep result from a mix of exposure to infectious microbes with a variety of additional factors such as poor nutrition, degraded or reduced habitat, human-caused stressors, extreme weather conditions, parasite loads, and the presence of domestic livestock (AXYS Environment Consulting Ltd., 2005). Variation in the interactions of these factors make it difficult to make simple conclusions on a single cause of wild sheep pneumonia as the relative importance of these factors will vary from case-to-case. The presence of the infectious agents on their own is rarely enough to cause wild sheep pneumonia outbreaks, but the presence of one or more of agents is necessary for disease to occur.

Ability to predict the contribution of various risk factors to pneumonia outbreaks remains limited due to the challenges of studying outbreaks in wild animals and variation in conditions between outbreaks. Factors limiting the investigation of bighorn sheep pneumonia include (Besser et al. 2008):

1) The remoteness of the areas where bighorn sheep live resulting in poor surveillance of causes of death;
2) Inevitable delays in discovering the sick or dead animals which reduces the quality of samples for laboratory testing; and
3) The use of conventional bacteriologic culture methods that may offer poor sensitivity for the detection of fastidious agents, often failing to detect the majority of the diverse microbes present in biological samples.

The infectious cause of wild sheep pneumonia has been debated since its initial discovery. A variety of parasites, bacteria and other agents have been implicated as the causes of wild sheep pneumonia. Appendix A summarize some of the available literature on infectious causes of wild sheep pneumonia. This table, while not an exhaustive list of all pathogens that can cause pneumonia in sheep, establishes that there are multiple agents that can infect both domestic and wild sheep, that there is evidence that wild sheep acquire those agents from domestic sheep, and that infection has been associated with diseases and/or population limiting effects in wild sheep.

Bighorn sheep can harbor pathogens associated with pneumonia without known exposure to domestic sheep and disease outbreaks in wild sheep have occurred without a known association with domestic sheep (Clifford et al. 2009). This demonstrates that it is unrealistic to conclude that the suite of factors that lead to wild sheep outbreaks are the same in all circumstances; that an infectious microbe is sufficent on its own to cause pneumonia and; that exposure to domestic sheep is necessary for all instances of wild sheep pneumonia.

Bighorn sheep respiratory disease has been regularly associated with *Mycoplasma ovipneumoniae* and leukotoxin-producing Pasteurellaceae bacteria, both of which offer considerable diagnostic challenges (USGS 2015). Besser et al. (2013) reviewed the evidence for each candidate primary agent in outbreaks of pneumonia in bighorn sheep with regard to causal critera including strength of association, temporality, plausibility, experimental evidence, and analogy. They found some degree of biological plausibility for all agents investigated and strong experimental evidence for *Mannheima haemolytica*. *Mycoplasma ovipneumoniae* was most strongly supported by all criteria in that study (Besser et al. 2013). Besser et al (2013) further proposed that bighorn sheep populations are naïve to *Mycoplasma ovipneumoniae* and its introduction results in epizootic polymicrobial bacterial pneumonia often followed by chronic infection in recovered adults. Domestic sheep and goats commonly carry *Mycoplasma ovipneumoniae* and *Mannheima haemolytica* and may not exhibit symptoms of disease (WSWG WAFA, 2016).

Lungworm (*Protostrongylus* spp) is a common parasite of wild sheep in North America which has been implicated in lungworm pneumonia complex (Foreyt et al. 2009; Forrester 1971; Spraker et al. 1984); however, it is difficult to directly attribute any lungworm species as a primary pathogen for pneumonia in sheep (Miller et al. 2012). All-age die-offs may be due to opportunistic bacterial infections that are secondary to lungworm lesions, however, the absence of apparent disease in free-ranging bighorn sheep experimentally inoculated with *P. stilesi* and *P. rushi*, as well as observations of bighorn sheep with respiratory disease and low pulmonary burdens of lungworm, raises doubt about the role of lungworm as primary pathogens (Miller et al 2012). The proportion infested with *Protostrongylus* spp. in many bighorn and thinhorn sheep populations in North America has been estimated to be 90-100% (Forrester 1971; Jenkins et al. 2005b; Pyus and Shave 1984; Uhazy et al. 1972).

One of the principal reasons some critics have questioned the role of contact with domestic small ruminants as a cause of wild sheep pneumonia is the challenge of fulfilling Koch's postulates for establishing causation (Wehausen et al. 2011). Koch's postulates propose that to identify an infectious organism as the cause of a disease, it is necessary to isolate the same organism from each case of the disease, and to produce that disease in an animal by inoculating it with that agent cultured from a diseased individual. The relevance of Koch's postulates to this case can be questioned because; 1) wild sheep pneumonia is multi-factorial, depending on interactions of differeing host, microbial, and environmental factors; 2) detecting and/or isolating pathogens that are present in wild sheep can pose significant technical difficulties; and 3) there can be interactions between organisms that occur under natural conditions that cannot be replicated in the laboratory (IOM 2004).

Because bighorn sheep and thinhorn sheep are genetically related, some have assumed that they share similar disease susceptibilities (Garde et al. 2005). It has been proposed that the reason disease often manifests in wild sheep but not domestic sheep exposed to the same pathogens at the same time is that domestic sheep (as a population) have been exposed over a longer period of time and have evolved some resistance to these pathogens but wild sheep, with less history of exposure have not had the opportunity to evolve similar tolerance (Garde et al. 2005). Thinhorn sheep live in more remote habitats than bighorn sheep. Their history of exposure to domestic small ruminants would be even more limited than that of bighorn sheep, suggesting even greater immunological vulnerability to pneumonia-causing pathogens (Garde et al. 2005).

Other circumstances or factors implicated as risk factors for wild sheep pneumonia include: 1) density-dependent forces such as food shortage or stress contributing to susceptibility to pneumonia (Monello et al. 2001); 2) translocations of wild sheep for conservation (Dubay et al. 2002); and 3) poor range condition, mineral deficiencies, and weather (Harris et al. 2011). The role for climate change in risk of wild sheep pneumonia is unknown. This may be of particular concern for thinhorn sheep where high latitude effects of climate change may influence movement and migrations, precipitation, forage quality and availability and interactions with other species; all with subsequent impacts on disease dynamics (WSWG WAFA 2015).

3.5 What are the standard management practices for wild sheep pneumonia?

A large number of field investigations, epidemiological studies, and models have established that bighorn sheep populations located closer to domestic sheep had smaller population sizes and lower population growth rates than populations further away and that pneumonia in bighorn sheep can result in significant long-term impacts on populations (Monello et al. 2001; USDA 2006). However, there remain debates regarding the necessary degree of separation needed to prevent transmission of pneumonia-casusing microorganisms. The degree of contact between bighorn and domestic sheep to result in catastrophic population effects varies with the status of the wild population and environmental variables. Some US bighorn sheep models suggest that <0.02 to 1.3 interspecies contacts per year results in a 50-70% chance herd extirpation within 70-100 years (Carpenter et al. 2014). Another study of an outbreak of pneumonia in bighorn sheep in Colorado combined laboratory evidence and field observations to conclude that introduction of a single domestic sheep into wild sheep range can result in increased adult mortality and reduced lamb recruitment for several years (George et al. 2008). Attempts to recover bighorn sheep populations (e.g. habitat improvements, augmenting local herds, and transloction to unoccupied habitats) have generally failed in areas where domestic sheep occurred (Clifford et al. 2009). As a result of strong supporting evidence, segregation of wild sheep from domestic sheep and goats is a cornerstone of preventing pneumonia in bighorn sheep, but specific distances of separation cannot be prescribed consistenly across all circumstances.

Policies and practices to separate wild and domestic sheep existed as early as the 1950's in the United States (USDA 2006). The 2012 Wild Sheep Working Group of the Western Association of Fish and Wildlife Agencies unanimously endorsed the conclusion that until it can be confirmed that thinhorn sheep are as or more naïve to pathogens from domestic sheep (compared to bighorn sheep) and the effects of exposure to infectious organisms can be fully understood, it is essential that no association occurs between thinhorn sheep and domestic sheep and goats. Risk assessment or management plans for thinhorn sheep in the Northwest Territories and in northern BC (Muskwa-Kechika) recommend avoiding contact between thinhorn and domestic sheep (Axys Environmental Consulting Ltd. 2005; Garde et al. 2005). A draft of the Province of British Columbia's (Ministry of Forest, Lands and Natural Resource Operations) order for management of Dall's and Stone's sheep winter range in the Skeena, Peace and Omineca Regions (#U-6-041) calls for no use of domestic sheep, goats or camelids for vegetation management or as pack animals and no issuance of range tenures for domestic sheep, goats or camelids within Dall's and Stone's sheep Specified Area (defined as the mapped thinhorn sheep herd range plus a 50 km buffer). The BC Forest Service policy on the use of sheep grazing in forestry states that it is important to ensure that there is no physical contact between domestic sheep and wild goats or sheep and that it may be necessary to stay out of all or a portion of a drainage or to modify the timing of a graze in areas populated by wild sheep and goats. Similar management recommendations have been made by many US state agencies as well as in the scientific literature.

Despite evidence that domestic sheep are a significant risk factor for disease and declines in bighorn sheep, the economic consequences of restricting domestic sheep grazing has polarized the debate on the necessary degree of separation (Clifford et al. 2009). The inability to definitively and consistently identify pathogens responsible for all bighorn sheep deaths following contact with domestic sheep does not discount other evidence that contact with domestic sheep results in a high probability of infection in bighorn sheep (Wehausen et al. 2011). Case studies and research showing that co-mingling of a small number of domestic sheep is sufficient to result in wild sheep disease suggests the need to prevent contact. However, the size of the buffer zone to preclude straying of domestic small ruminants into wild sheep range (or vice versa) is likely affected by landscape characteristics and movement patterns of animals – both of which can vary seasonally, by species and by terrain and weather.

4. RISK ANALYSIS

For a population to be at risk, it must be exposed to sufficient amounts of a hazard that can cause negative effects of sufficient magnitude to require management and few, if any, effective and acceptable options to mitigate those effects exist. Risk can be accentuated when there is a high degree of uncertainty about the likelihood or impacts of an effect and/or something highly valued is at risk. Therefore, risk assessment focuses on understanding the following: 1) if a hazard is present; 2) if the population of concern is suspectible to the effects of the hazard; 3) if the population of concern is likely to be exposed to enough of the hazard to produce an effect; 4) if the magnitude of that effect is at unacceptable level; 5) if there are ways to prevent, treat, or reverse the effects and; 6) the level of uncertainty compared to what is at risk. The risk assessment process is intended to organize and make explict information that can be used to make these deteminations.

Risk assessments were created first to examine the possible effects of environmental chemicals. In those situations, laboratory experiments, the nature of casual relationships and the biomedical models made quantitative risk assessment more reliable and reproducible. Risk assessments of disease in free-ranging wildlife rarely have the same level of data, certainty in causal relationships and repeatability as can be achieved in chemical risk assessments. Risk assessments in wildlife health, therefore, tend to be qualitative or, when quantitative, still require judgements on tolerance for the likelihood, magnitude, and uncertainty of an effect. The goal of this risk assessment is to summarize the evidence associated with the major determinants of risk (exposure, magnitude, mitigation, and uncertainty) to provide a shared understanding of the circumstances and to facilitate evidence-based management decisions. We undertook this process by addressing a series of questions as follows:

QUESTION #1: ARE PNEUMONIA-CAUSING PATHOGENS PRESENT IN YUKON AND NORTHERN BRITISH COLUMBIA?

There is no systematic or ongoing surveillance of disease in thinhorn or domestic sheep in Yukon or northern BC. All reported cases of disease are derived from limited surveys and opportunistically found animals. There is a high likelihood that most cases of death and disease in Yukon thinhorn sheep have gone undetected due to their remoteness from people, challenges in finding sick or dead wildlife, and infrequency of surveys.

The Canadian Wildlife Health Cooperative maintains a national database of reports of causes of death or disease in wild animals from across Canada. Entries into the database come from animals that have been opportunistically found and submitted to affiliated animal health labs, as well as, animals collected as part of active surveys for disease. We searched the CWHC database for cases of wild sheep pneumonia from 1996 to present from Yukon, Northwest Territories and northern British Columbia. There were 43 relevant submissions, one bighorn sheep, 32 Dall's sheep, 8 Stone's sheep, and two domestic sheep (Table 5).

Of the 43 submissions, 12 had diagnoses relating to pneumonia (bronchopneumonia, pleuropneumonia or verminous pneumonia) including one domestic sheep from northern BC, one Stone's sheep from BC and 10 Dall's sheep (N=2 Yukon, N=8 NWT). Of these 12 pneumonia diagnoses one Dall's sheep from NWT was listed as "very suggestive of subacute Pasteurella or mixed bacterial infection." The only other non-verminous pneumonia diagnosis was attributed to infection by *Pasteurella multocida* in a Dall's sheep from NWT. For verminous pneumonia diagnoses, *Protostrongylus odocoilei* (lungworm) was identified in one case, *P. stilesi* was identified in six cases, the remaining cases either did not identify the species or listed *Protostrongylus* spp.

Table 5: Summary of results from sheep case reports in the CWHC's national database for Yukon (YK), Northwest Territories (NWT) and northern British Columbia (N BC).

Common name	Species	# tested YK	# tested NWT	# tested N BC	Total tested	% (n/N) with pneumonia*
Bighorn sheep	*O. canadensis*	0	0	1	1	0 (0/1)
Dall's sheep	*O. dalli*	12	14	6	32	84 (10/12)
Stone's sheep	*O. dalli stonei*	1	0	7	8	100 (1/1)
Domestic sheep	*O. aries*	0	0	2	2	50 (1/2)
Total		**13**	**14**	**16**	**43**	**28 (12/43)**

*pneumonia was not necessarily the primary cause of morbidity/mortality

The Animal Health Unit of the Government of Yukon had four case reports recorded of thinhorn sheep (1 Stone's sheep, 3 Dall's sheep); gross necropsies were conducted between December 2012 and September 2015. Three of the four specimens were found dead, one was submitted by a hunter because he noticed white areas in the lungs. The Stone's sheep was a juvenile, the Dall's sheep varied from 4 months old to 11 years old. Animals varied in body condition from emaciated to what would be considered good body condition for the age and time of year. All of the four gross necropsy reports noted changes in respiratory tissues; several had indications of lungworm infection that appeared to be secondary to other causes of death (ie. trauma in one, possibly neoplasia in another). Additional analysis (ie. histopathology, parasitology, etc) was conducted on these cases by the Canadian Wildlife Health Centre and are captured in results in the above table.

Work done in the 1980's found no evidence of *Mycoplasma ovipneumoniae* in wild Dall's or Stone's sheep (Zarnke & Rosendal, 1989).

Other studies have also demonstrated the presence of lungworms in Dall's sheep in Yukon, northern BC, and NWT (Hoberg et al. 2002; Jenkins et al. 2005; Jenkins et al. 2007; Kutz et al. 2001). Jenkins et al (2000) also found evidence of *Mannheimia hemolytica* and *Arcanobacterium pyogenes* in two adult Dall's sheep in the Northwest Territories. Immunohistochemistry of pneumonia-causing bacteria (*Mannheimia haemolytica*, *Mycobacterium* sp.), and viruses (parainfluenza-3, bovine herpes virus type 1, bovine respiratory syncytial virus, bovine viral diarrhea) was performed on these two NWT Dall's sheep. All results were negative with the exeption of one of the ewes being positive for *Mycobacterium* sp. (Jenkins et al. 2000). Although results for the cattle viruses were negative by immuno-histochemistry, Jenkins et al (2000) could not rule out a viral contribution to these two pneumonia cases due to limitations of the test (serology would have been able to confirm exposure to these viruses). Serological testing in thinhorn sheep for pneumonia-causing viruses from domestic sheep or cattle (ie. Parainfluenza-3) may elucidate the exposure history in the region and potential for exposure of herds in Yukon and northern BC.

There have been limited health surveys conducted in Stone's sheep (Axys, 2005; Jenkins & Schwantje 2004; Jenkins et al. 2007). Axys (2005) summarizes health findings from a two-year parasite survey conducted of three herds in the Muskwa-Kechika Management Area in BC and a summary from a telemetry survey of herds in the Williston Lake area in northern BC. It concluded from the baseline survey that the internal parasites of Stone's sheep was similar to other wild sheep, with some differences in fauna and seasonal shedding. Jenkins and Schwantje (2004) found high prevalence of *Protostrongylus* spp (50-95%) and *Paraelaphastrongylus odocolei* (muscleworm) (75%) in sampled Stone's sheep herds in northern BC. Bacterial pathogens that cause pneumonia, including *Pasteurella trehalosi*, *Mannheimia haemolytica*, and *A. pyogenes*, have also been isolated from several herds in Northern BC (Schooler/Dunlevy herds) (Demarchi & Hartwig, 2004).

Axys (2005) cites an Alaskan serological study revealing evidence of several pneumonia-causing pathogens in Dall's sheep (infectious bovine rhinotracheitis, parainfluenza 3, respiratory syncytial virus). The original citation for this finding was not available for review, preventing an assessment of the sensitivity and specificity of the serological tests used in this study or proportions of animals that tested positive. Another Alaskan study using indirect hemagglutination tests on sera from 251 Dall sheep from interior Alaska collected during the period 1979 to 1987 revealed no evidence of exposure to *Mycoplasma ovipneumoniae* (a pneumonia-causing pathogens thought to be a central pathogen in bighorn sheep die-offs (Zarnke and Rosendal, 1989).

Question #2: Are thinhorn sheep in Yukon and northern British Columbia susceptible to adverse effects of pneumonia?

There are several lines of evidence to conclude that thinhorn sheep can get pneumonia but the population effects in thinhorn sheep can only be evaluated based on effects of pneumonia in other wild sheep.

Case reports of pneumonia in thinhorn sheep exist

Literature indicates that thinhorn sheep are susceptible to pneumonia-causing agents, in particular, lungworms and *Pasteurella* sp (Miller 2001). Pneumonia was diagnosed as the primary cause of mortality in Dall's sheep in 1999 from two ewes from the Mackenzie Mountains in the Northwest Territories (Jenkins et al 2000). Although few in number, case reports demonstrate that thinhorn sheep (both Dall's and Stone's sheep) in Yukon are susceptible to pneumonia (CWHC database search and necropsy reports from Government of Yukon). It could not be determined from these reports whether pneumonia was a primary or secondary cause of morbidity or mortality.

In a case study described by Black et al (1988), it was shown that Dall's sheep in captivity developed pneumonia after being exposed to domestic sheep. All exposed sheep developed severe respiratory signs refractory to anthelmintic and antibiotic therapy (Black et al. 1988). It was possible to isolate both, or one of, *Mycoplasma ovipneumoniae* and *Mannheimia* (Pasteurella) *hemolytica* in some of the Dall's sheep. It was difficult to generalize the results as testing varied by animal. However, *Mycoplasma ovipneumoniae* was isolated from 2 of the 6 domestic sheep (Black et al. 1988).

Dall's sheep have been shown in laboratory experiments to be equally or, potentially, more susceptible to variants of *Mannheimia* (Pasteurella*) haemolytica* than bighorn sheep (Foreyt et al 1996). Injection with *M. haemolytica* variant caused pneumonia and resulted in death (or euthanasia) in two out of three Dall's sheep, whereas; none of the bighorn or domestic sheep developed pneumonia (Foreyt et al 1996).

Hengeveld and Cubberley (2012) report on results of tests undertaken on Stone's sheep in the Muskwa-Kechika management area. Of 52 dead animals examined, avalanches were responsible for the majority of deaths. Poor body condition was common in these dead animals. Examination of animals in this area for gastrointestinal parasites and lungworm revealed findings as to be expected for wild sheep (details not provided); they noted that lungworm was common and sporadic cases of winter ticks could be found.

Garde et al (2005) conducted a risk assessment of pathogens that could affect Dall's sheep in the Northwest Territories. They concluded that there were nine pathogens of greatest concern and qualitatively assessed them by combining probability of transmission and the extent of impact (See Table 6). In addition, Garde et al (2005) listed 19 pathogens of unknown risk to Dall's sheep in NWT. These pathogens had insufficient information on transmission dynamics and risks and potential impact(s) on wild sheep.

Table 6: Pathogens of greatest or unknown risk to Dall's sheep in the Northwest Territories from risk assessment by Garde et al (2005).*

Pathogen	**Potential to cause pneumonia in wild sheep**	**Probability of transmission to Dall's sheep from domestic sheep**[◊]	**Health impact on Dall's sheep**[◊]
Highest risk pathogens			
Mycobacterium avian paratuberulosis	No	Moderate	Moderate
Mycoplasma conjunctivae	No	Unknown	High
Mycoplasma ovipneumoniae	**Yes**	High	High
Pasteurella sp.	**Yes**	High	High
Mannheimia haemolytica	**Yes**	High	High
Contagious ecthyma	No	High	High
Parainfluenza-3	**Yes**	Unknown	High
Muellerius capillaris	**Yes**	High	Moderate
Oestrus ovis	No	High	High
Pathogens of unknown risk to Dall's sheep			
Chlamydophila sp.	**Yes**, *C. pecorum*	Insufficient information to assess probability and impact	
Corynebacterium pseudotuberculosis	No		
Coxiella burnetti (Q-fever)	No		
Erysipelothrix rhusiopathiae	No		
Mycoplasma arginini	**Yes**		
Mycoplasma mycoides	**Yes**		
Adenovirus	**Yes**		
Border Disease Virus	No		
Bovine Viral Diarrhea Virus	No		
Corona virus	**Yes**		
Epizootic hemorrhagic disease virus	**Yes**		
Bluetongue virus	**Yes**		
Infectious bovine rhinotracheitis	**Yes**		
Respiratory Synctial Virus	**Yes**		
Paraelaphostrongylus odocoilei	**Yes**		
Various gastrointestinal parasites and ectoparasites	No		

Pathogen	Potential to cause pneumonia in wild sheep	Probability of transmission to Dall's sheep from domestic sheep◊	Health impact on Dall's sheep◊
Eimeria sp.	No		
Neospora caninum	No		
Sarcocystis sp.	No		
Scrapie	No		

*all pneumonia-causing pathogens listed here are listed in Appendix A
◊ Ratings were made by Garde et al (2005)

Are thinhorn sheep suspectible to the co-factors that affect the probability of pneumonia?

There has been minimal research or surveillance on risk factors for wild thinhorn sheep in Yukon and northern British Columbia to ascertain the degree to which co-factors are present or absent in these herds. Nor has there been any pneumonia-related die-offs in thinhorn sheep herds from which to glean information about the various co-factors.

Environmental factors that could affect, either directly or indirectly, the susceptibility of wild sheep to pneumonia have been described in detail by Miller et al (2012). Monello et al (2001) assessed the relationship between bighorn sheep die-offs from pneumonia and environmental and biological factors. They found that the strongest associations with die-offs were from proximity to domestic sheep and density-dependant factors such as food shortage and stress.

No evidence could be found to indicate that there has been contact between domestic and wild sheep populations in Yukon. Although, accurate numbers and distribution of domestic sheep in Yukon could not be found, we estimated that there are approximately 100 sheep in the territory, with most sheep farms located in close proximity to Whitehorse (see Figure 1). The health status of domestic sheep in Yukon is unknown and there was no diagnostic information available to review. Fencing and separation from wildlife practices on sheep farms are unknown. There were no reports of domestic sheep grazing rights being extended, or even applied for, on Crown land (Kevin Bowers, Government of Yukon. personal communication). Applications for grazing include criteria to assess location, species, season of use, and animal density. The majority of grazing applications received by the Government of Yukon were for horses, with only two applications for cattle (Kevin Bowers, Government of Yukon. personal communication). Applications to purchase Crown land for agricultural or other uses are reviewed by the Yukon Environmental and Socio-econonmic Assessment Board; which has government representation from Departments of Environment and Agriculture, as well as, representation by First Nations, and members of the public. They consider heritage aspects, impacts on wildlife, environmental impacts, and other criteria in their assessment. The application of this process to Yukon sheep farms could not be determined.

Climate change may influence susceptibility characteristics in thinhorn sheep populations (e.g. patterns of movement, forage quality, interactions with other species), as well as pathogen-related factors (e.g. agent survival, diversity, and abundance). It is well recognized that the north is experiencing more dramatic effects of climate change than other, more southern, latitudes; average temperatures in the Arctic have increased at twice the rate of the global average. Kutz et al (2009) highlight the potential for changes in host-parasite interactions as a result of climate change including both endemic hosts and parasites (e.g. sheep muscleworm, *P. odocoilei*) and the potential for invasion of new hosts or parasites (e.g. ticks).

Researchers have linked climate alterations to changes in disease patterns. For example, a pneumonia die-off in muskoxen in Norway has been linked to high humidity and temperatures (Ytrehus et al. 2008) and declining moose populations have been associated with physiological changes from climate change that alter disease susceptibility patterns (Murray et al 2006). It is unknown whether there have been changes in Yukon thinhorn sheep behaviours or characteristics or in pathogens of consequence for sheep in Yukon as a result of climate change. Kutz et al (2009) discuss changes in the distribution of winter ticks that affect elk in Yukon; however, this might be a case of pathogen introduction due to translocations of elk from Alberta rather than a response to climate change.

Due to more suitable climate conditions, it is probable that agriculture will expand in northern Canada, including the Yukon. This growth may include an increase in sheep production but no documented plans for expansion of small domestic ruminant indusrry in Yukon could be found.

Other environmental factors that could affect disease susceptibility in thinhorn sheep such as soil selenium levels, water availability, forage quality, abundance, and availability, and weather characteristics have not been examined for this report due to the request to focus on pneumonia-causing pathogens.

The host factors that could affect susceptibility to disease in wild thinhorn sheep include features such as behavior, nutritional status, age, genetics, immune status (e.g. innate resistance (ie. mucociliary barriers), passive immunity (neonates), and previous exposure), physiology (e.g. production and reproductive state, disease status, and stress). Information about the immune status of thinhorn sheep populations in Yukon to respond to pneumonia-causing pathogens could not be located. The types of potential anthropogenic drivers of physiological stress or negative health-related behaviours in thinhorn sheep in Yukon and northern BC might include, but is not limited to: construction of roads, mining activities, environmental toxins, hunting, and tourism.

Do thinhorn sheep experience population limiting effects from pneumonia?

Population level die-offs due to pneumonia, such as those that have been reported in bighorn sheep, have not been reported in wild thinhorn sheep (Bowyer & Leslie 1992; Garde et al 2005; Jenkins et al. 2000; Nichols & Bunnell 1999; Simmons et al. 1984). This may reflect difficulties in accessing thinhorn sheep to monitor causes of death; lack of outbreaks of pneumonia in thinhorn sheep do to lower rates of exposure to pathogens, or to different responses to pneumonia-causing agents.

QUESTION #3. DO THE CONDITIONS AND CIRCUMSTANCES EXIST FOR YUKON THINHORN SHEEP TO BE EXPOSED TO PNEUMONIA-CAUSING ORGANISMS FROM DOMESTIC SHEEP?

The presence, distribution, or prevelance of pneumonia-causing organisms in domestic sheep in Yukon cannot be established because there is no ongoing surveillance of small ruminant diseases, veterinary services are sparse, and we were unable to obtain any reports of surveys or pathological investigation of diseases in domestic sheep.

The estimated small number of domestic sheep and goats in the Yukon plus their concentration in a very small portion of the territory suggest few opportunites for thinhorn sheep-domestic small ruminant contact. There is no complete census of domestic sheep or sheep grazing movements in the territory, preventing a conclusion that there is no overlap. Documented plans for expansion of domestic sheep farms or locations of current or planned grazing ranges were not available, therefore, the potential for co-mingling of domestic sheep and thinhorn sheep could not be established. There is anecdotal information that there is some interest in the agricultural community in Yukon Territory to increase domestic sheep production (Jane Harms, Government of Yukon. personal communication).

Other potential reservoirs of pneumonia-causing pathogens include cattle, goats, wild ungulates, and domestic camelids (Dixon et al. 2002; Kutz et al. 2002; Wolfe et al. 2010). Detailed exploration of these reservoir hosts is beyond the scope of this project. A 2003 assessment of the risk to BC wildlife from camelids concluded that:

> *"Risks from camelids to wildlife in British Columbia remain hypothetical … as no direct evidence was found to implicate camelids as sources of significant diseases in wildlife in BC or elsewhere. There is a sound basis in the literature and the basic principles of epidemiology to raise the concern that domestic species in wilderness areas can introduce disease agents that can have important effects on local wildlife populations. This concern is greatest for wildlife populations already dealing with other population stressors at the time of pathogen or parasite exposure. There is insufficient data to accurately forecast the probability of disease transmission or to predict its effects; therefore, uncertainty remains an important determinant of risk in this situation. There is sufficient basis for concern to advise a precautionary approach to managing disease risks to wildlife from camelids."* (Schwantje & Stephen 2003)

Although there is currently limited overlap between their ranges, muskox are known to harbour lungworms, particularly *Protostrongylus stilesi,* that are infectious to thinhorn sheep (Kutz et al. 2002). However, *P. stilesi* is considered to be widespread in some Dall's sheep populations in NWT (Jenkins et al. 2000). It is unknown if muskox are suitable hosts for the muscleworm of concern in thinhorn sheep, *P. odocoilei,* however, with the expansion of the muskox range that is occurring, there is some concern they may serve to bridge the gap between thinhorn sheep herds that are naïve to this parasite (Jenkins et al. 2005b).

Studies have experimentally commingled bighorn sheep with a variety of species including domestic sheep, cattle, horses and goats, and wild elk, mountain goats, and deer (Besser et al. 2012b). As reported elsewhere, there was significant disease transfer from domestic sheep to the bighorn sheep. However, these studies showed that there was no transmission of disease from wild ungulates but that there was disease transmission (*Pasteurella* sp.) between domestic cattle, horses, and goats (Foreyt et al. 2009; Foreyt & Lagerquist 1996).

QUESTION #4: WHAT IS THE POTENTIAL MAGNITUDE OF EFFECTS OF A PNEUMONIA OUTBREAK IN THINHORN SHEEP?

There is no evidence to directly answer this question. However, there is supporting information to to reasonably assume that if a pneumonia outbreak were to occur in thinhorn sheep populations that the magnitude of the effect could be severe due to: 1) the experimental observation of increased immune response (neutrophils) in Dall's sheep as compared to bighorn sheep and domestic sheep (Foreyt et al. 1996); 2) thinhorn sheep social structure would allow exposure between and within thinhorn groups after intial exposure to domestic small ruminant pathogens; 3) biological and genetic similarities between thinhorn sheep and bighorn sheep, which have experienced substantial effects from pneumonia (Bowyer & Leslie 1992); and 4) the naïve immunity of wild thinhorn sheep to one of the key pathogens of concern, *Mycoplasma ovipneumoniae* (Foreyt et al. 1993; Jenkins et al. 2000; Zarnke & Rosendal, 1989).

QUESTION #5: CAN EFFECTS OF OR RISK OF PNEUMONIA IN WILD SHEEP BE PREVENTED, TREATED, OR MITIGATED?

ARE THERE VACCINES OR TREATMENTS AVAILABLE THAT CAN BE EFFECTIVELY DELIVERED?

No effective vaccines for wild or domestic sheep are available. Vaccination of wildlife has generally been shown not to be feasible, efficient, or effective; with rabies providing one possible exception to this statement (Miller et al. 2012). The multi-factorial nature of sheep pneumonia would complicate the development of a universally effective vaccine (Wehausen et al. 2011; Clifford et al 2009).

It has been proposed that it may be possible to protect the health of wild sheep by vaccinating domestic sheep for one of the potentical causes of pneumonia, *Mycoplasma ovipneumoniae* (Zeigler et al. 2014). Zeigler et al (2014) showed that immunization with large antigenic mass combined with adjuvant could induce a strong antibody response in ewes which passively immunized lambs. In the model presented by Besser et al (2013) efforts to control the disease through the use of a vectored vaccine for Pasteurellaceae are unlikely to provide significant benefits. However, they do identify that efforts to segregate healthy bighorn sheep populations from *Mycoplasma ovipneumoniae*-infected reservoir hosts as critical to the prevention of new disease epizootics. *Mycoplasma ovipneumoniae* vaccines or other management strategies could aid in reducing the impact of pneumonia in bighorn sheep (Besser et al 2013) but there are significant challenges to delivering vaccination programs in free ranging wildlife, particularly in remote locations. Wehausen et al (2011) summarize research on vaccines against various strains of *Mannheimia haemolytica* and other *Pasteurella* sp; none of the studies produced effective, long-lasting protective immunity and, in some cases, resulted in higher infection rates in vaccinated animals than unvaccinated animals. We were unable to find reference to an effective wild sheep vaccination program.

As a part of the Growing Forward 2 inititative (2013-2018) the Yukon Territory has recently launched the Yukon Livestock Health Program. The objective of the program is to "monitor, support, and improve the health and welfare of Yukon livestock including poultry, swine, cattle, small ruminants (goats and sheep), horses, and game farmed species." Eligible activities include: education for veterinarians, producers, and the public; livestock health/veterinary support for producers including a herd health visit by a veterinarian to the farm to assess the farm and livestock and a follow up visit; and the development of a Yukon Livestock Health Database. By enrolling in the Yukon Premises ID Program, producers can access the veterinary support of the program including up to two veterinary visits per year at no cost. Private veterinarians can work as partners with the Animal Health Unit and Agriculture Branch to provide care and herd helth support funded through the Livestock Health Program. Veterinary services were identified as one of the constraints to sheep and goat development in the Multi-Year Development Plan for Yukon Agriculture and Agri-Food 2008-2012 prepared in 2007. To date, 13 farms have registered for this program. It was unknown at the time of writing how many of these farms were raising sheep and how many vet visits were conducted to provide advise or treatment for sheep.

ARE THERE OTHER MITIGATION STRATEGIES THAT CAN PREVENT PNEUMONIA TRANSMISSION TO WILD SHEEP?

The single most important preventive approach, which is accepted and recommended by researchers, biologists, and wildlife managers is the separation of domestic and wild sheep (George et al. 2008; Schommer & Woolever 2001; Wehausen et al. 2011).

There are several studies that have developed predictive models to assess the effectiveness of different management options that allow for continued domestic sheep grazing in shared areas in order to prevent pneumonia transmission from domestic sheep to bighorn sheep (Carpenter et al. 2014; Clifford et al. 2009). Clifford et al (2009) assessed three management strategies in their models including: 1) reducing grazing areas for domestic sheep; 2) reducing grazing time on high risk allotments; and 3) improving stray domestic sheep management. Their findings show that none of these strategies would adequately lower the risk of disease transmission between domestic and wild bighorn sheep and, therefore, concluded that domestic sheep grazing should not occur in known bighorn sheep ranges. Carpenter et al (2014) generated disease risk models based on varying probabilities of contact between domestic sheep grazing in allotments in the Payette National Forest in Idaho where bighorn sheep range and, from there, estimated probabilities of bighorn herd extirpations when pneumonia die-off occur from interspecies contact. They reported from this study that, should domestic sheep continue to graze in allotments in this area, herd extirpation rates would range between 20 and 100% depending on contact probabilities between domestic and wild sheep.

Recommendations on the distance of buffer zones around wild sheep territories are varied and range from 3.2 kms to 50 kms (Bighorn Desert Council 1990; Clifford et al. 2009; Government of BC 2016). To the best of our knowledge, the Government of Yukon does not have a fixed buffer distance that it recommends specifically to prevent transmission of pneumonia causing agents.

Yukon's Growing Forward 2 (2013-2018) program provides funding to assist farmers with fencing their land. Although the aim of the project is to prevent crop damage from wildlife, fences may protect thinhorn sheep populations from contact with domestic livestock. It is unknown what the level of uptake there has been from this fencing program.

QUESTION #6: WHAT ARE THE UNCERTAINTIES IN ESTIMATING PROBABILITY OF EXPOSURE OF THINHORN SHEEP TO PNEUMONIA-CAUSING PATHOGENS FROM DOMESTIC SHEEP AND THE POTENTIAL IMPACTS FROM TRANSMISSION?

A reliable, evidence-based risk assessment of the health risks to wild thinhorn sheep from domestic sheep cannot be performed with the existing information and data. As discussed above, risk is the combination of the likelihood of occurrence of an adverse event and the magnitude of the consequences (Zepeda et al 2001). The estimation of risk also involves objectively summarizing the uncertainties that underlie assessments of probability and consequences.

The framework that is commonly used and promoted by the World Organization for Animal Health (OIE) to assess risks in animal populations involves three components: release, exposure, and consequence assessments (Zepeda et al 2001). The release assessment determines whether the disease is present (or potentially present) in the geographic location (Yukon and northern BC) and species of interest (domestic sheep). The exposure assessment describes the pathways of exposure and associated probabilities that could cause infection in other populations (wild thinhorn sheep in Yukon and northern BC). The consequence assessment describes the biologic (i.e. mortality and morbidity rates) and socio-economic (i.e. reduced revenue from wildlife-oriented business, trade restrictions,) impacts should the disease occur in wild thinhorn sheep (Zepeda et al, 2001).

Table 7 outlines the data requirements for risk assessment and uncertainty analyses. For this risk assessment most of the data requirements simply cannot be met with the available information. In addition to the information gaps identified in Table 7 for Yukon, there are also uncertainties as to the relative importance and role of various microbial, biological, and environmental factors that lead to bighorn sheep die-offs from pneumonia (Besser et al. 2013; Miller et al. 2012; Monello et al. 2001; Wehausen et al. 2011) and significant gaps about the epidemiology and impact of pneumonia in thinhorn sheep, as described above.

Table 7: Information requirements for risk assessment and uncertainty analyses

Risk assessment steps	Epidemiological components	Data/knowledge requirements	Data available for Yukon *
What are the potential pneumonia-causing pathogens that could affect wild sheep? (Hazard identification)	List of pathogenic agents that could be associated with pneumonia in sheep	Endemic pathogens	No surveillance, a few case reports
		Emerging pathogens	No surveillance
		Epidemiology of each pathogen	Limited to isolated surveys, for the most part focused on a subset of pathogens.
	Knowledge on the presence or absence of pathogen in Yukon	Methods to demonstrate absence of pathogen	Insufficient testing
What is the presence of pneumonia-causing pathogens in domestic sheep? (Release assessment)	Prevalence of pathogen in North America and in Yukon, specifically	Survey and surveillance results	No surveillance, no case reports available
		Survey methodology	No surveys conducted
		Confidence level, precision, expected prevalence	Unknown
		True prevalence	Unknown
	Epidemiological characteristics of the disease and the pathogen	Incubation	Variable
		Carriers	Variable
		Morbidity	Inadequate information
		Mortality	Inadequate information
		Method of spread	Variable
		Pathogenesis	Variable
		Target organs	Variable
		Susceptible species	Variable
	Diagnostic tests	Test sensitivity and specificity	Inadequate information
What is the probability of transmission of pathogens from domestic sheep	Characteristics of the susceptible populations and environmental factors	Pathways of exposure	Variable
		Herd densities	Information available
		Herd distributions	Information available
		Contact rate, and nature of contact of wild	Unknown but likely low at the present

Risk assessment steps	Epidemiological components	Data/knowledge requirements	Data available for Yukon *
to wild thinhorn sheep in Yukon and northern BC? (Exposure assessment)		thinhorn sheep with domestic sheep	
		Immune status	Unknown
		Presence of other host and environment co-factors	Limited information
What would the impacts be if thinhorn sheep herds were exposed to pneumonia-causing pathogens? (Consequence assessment)	Biologic and economic consequences	Method of spread	Variable
		Morbidity	Unknown
		Mortality	Unknown
		Number of animals at risk	Information available
		Socio-economic impact	Limited information available
		Cost of control and eradication	Information from other jurisdictions
		Feasibility of control	Information from other jurisdictions

* the term “variable” refers to either 1) that the quantity or quality of information was variable amongst the different pathogens wherein we knew significantly more about a small subset of pathogens than for all identified infectious agents or 2) that the nature of the data varied with the context in which the pathogen was found (ex. impacts of a pathogen varied with immune status).

5. Risk analysis conclusions

5.1. CONCLUSION #1: The exact nature of the risk of pneumonia of thinhorn sheep acquired from domestic sheep cannot be determined for the Yukon and northern British Columbia due to limits in available information.

5.1.1. There is insufficient information specific to thinhorn sheep in Yukon and northern British Columbia

The risk of pneumonia from domestic small ruminants to thinhorn sheep in the Yukon and northern British Columbia cannot be quantified because of insufficiencies in the amount and nature of evidence specific to the region on; 1) the distribution of domestic and thinhorn sheep, particularly how those distributions overlap creating exposure potentials; 2) the lack of data on the prevalence, distribution or causes of disease and death in both thinhorn and domestic sheep in Yukon and northern BC, particularly on the occurrence and impacts of pneumonia-causing micro-organisms; 3) the lack of information available for this analysis on any planned expansion of the domestic sheep industry; 4) and the lack of available information on the economic and social values of the domestic sheep and thinhorn sheep industries.

A lack of information on the effects of pneumonia on thinhorn sheep is partly due to the remote nature of these animals (reducing opportunities to study wild-domestic sheep interactions); partly due to most scientific attention being placed on bighorn sheep (because of the readily observed and regular outbreaks of pneumonia in that species); and partly due to the lack of disease surveillance in thinhorn sheep. As a high mountain species, it can be expected that thinhorn sheep will be vulnerable to the predicted effects of climate change in Yukon and northern BC and that those impacts will effect disease risk in an unpredictable way. Because of these uncertainties, assignment of a qualitative risk to this situation is subject to personal or organizational risk perception and a quantitative risk assessment is not possible.

5.1.2. The multi-factorial nature of sheep pneumonia combined with lack of research and experience with pneumonia in thinhorn sheep cautions against directly assigning risks calculated for bighorn sheep to thinhorn sheep in Yukon and northern BC

No two wild sheep pneumonia outbreaks are the same. Known risk factors vary across populations and interact differently in different situations. Differences do exist between bighorn and thinhorn sheep ecology. The history of interactions between wild sheep and domestic small ruminants in northern versus southern Canada differ, creating different risk scenarios. It is biologically plausible to assume that risk factors differ in magnitude and probability between bighorn and thinhorn sheep. For example, 1) thinhorn sheep in Yukon and northern BC currently have less exposure to domestic small ruminant pathogens due to the small number of domestic small ruminants in the area, reducing thinhorn probability of exposure; 2) differences in immune system status may influence the probability that exposure to a pathogen will result in disease; 3) there may different probabilities of spread of disease in thinhorn sheep due to differences in their population densities and geographic connectivity compared to bighorn sheep; and 4) the intensity and frequency of exposure to domestic sheep pathogens needed to initiate an outbreak may differ due to different epidemiological characteristics and stressors. None of these difference have been quantified nor has the magnitude of effects of a pneumonia outbreak in thinhorn sheep; therefore preventing direct application of estimated risks for bighorn sheep to thinhorn sheep.

5.2. *CONCLUSION #2*: There is sufficent evidence and opinion to conclude that the unquantified risk to thinhorn sheep from pneumonia associated with domestic small ruminant exposure warrants a proactive management response in Yukon and northern British Columbia

5.2.1. There is widespread scientific evidence and professional opinion that domestic sheep are a significant risk factor for pneumonia in bighorn sheep and subsequently an impediment to species conservation and recovery.

Reducing, preventing, and eliminating the risk to wild bighorn sheep in western North America from pneumonia acquired from domestic small ruminants is a cornerstone of bighorn sheep conservation. Despite debates about the precise mechanisms of microbial causation and the exact proportional contribution of domestic animals to this risk, it can be concluded that the presence of policies and practices to separate bighorn and domestic small ruminants in multiple jurisdictions across western Canada and the United States is evidence that the burden of opinion is that this risk is sufficiently large to require management, even if it causes some economic losses to the domestic small ruminant sector.

5.2.2. There is no evidence to reject the conclusion that it is highly likely that thinhorn sheep are susceptible to the domestic sheep pathogens that cause pneumonia in individual animals and subsequent population limiting effects.

There is evidence and opinion to support the conclusion that thinhorn sheep have vulnerabilities and exposure pathways that would result in pathogen transmission from contact with domestic animals (WSWG WAFA 2016). Thinhorn sheep can die from pneumonia-causing pathogens that are associated with domestic sheep. The physiological similarities and similar pathogen exposure histories between bighorn and thinhorn sheep supports conclusions that they have similar immunological capacity (or lack of capacity) to cope with infections from pneumonia causing pathogens. The more remote nature of thinhorn sheep habitat further suggests that they have had less exposure to domestic animals pathogens and thus may be more immunologically naïve and therefore, more susceptible than bighorn sheep to infections after exposure to domestic animal pathogens. The social and movement behaviour of thinhorn sheep compared to bighorn sheep may cause differences in the exposure and likelihood of disease spread or persistence after an initial exposure to domestic small ruminant pathogens.

5.2.3. The magnitude of possible effects and lack of ability to mitigate the population limiting effects in wild sheep makes this a risk that requires proactive management attention, despite the current low probability of exposure.

It can be concluded that the potential magnitude of an outbreak of pneumonia in thinhorn sheep could be high due to: 1) evidence that thinhorn sheep can develop fatal disease after exposure to domestic sheep respiratory pathogens; 2) the existence of population limiting outbreaks of pneumonia in bighorn sheep under varying ecological and epidemiological situations; 3) assumed (but unproven) greater susceptibility of thinhorn sheep to domestic sheep pathogens due to the lack of historic contact between these species; and 4) the geographic connectivity of thinhorn sheep, creating a larger likelihood of spread and persistence of infection in a population. It can also be concluded that viable mitigation options do not exist (see below).

5.3. *CONCLUSION #3*: Preventing exposure of thinhorn sheep to domestic sheep is a reasonable management response

5.3.1. The bulk of professional opinion argues for a precautionary approach that includes separation of wild sheep and domestic small ruminants as the cornerstone of risk management. This includes existing recommendations affecting northern British Columbia.

The 2012 Wild Sheep Working Group of the Western Association of Fish and Wildlife Agencies unanimously endorsed the conclusion that until it can be confirmed that thinhorn sheep are as, or more, naïve to pathogens from domestic sheep (compared to bighorn sheep) and the effects of exposure to infectious organisms can be fully understood, it is essential that no association occurs between thinhorn sheep and domestic sheep and goats. Risk assessment or management plans for thinhorn sheep in the Northwest Territories and in northern BC (Muskwa-Kechika) recommend avoiding contact between thinhorn and domestic sheep. A draft of the Province of British Columbia (Ministry of Forest, Lands and Natural Resource Operations) order for management of Dall's and Stone's sheep winter range in the Skeena, Peace and Omineca Regions (#U-6-041) calls for no use of domestic sheep, goats or camelids for vegetation management or as pack animals and no issuance of range tenures for domestic sheep, goats or camelids within Dall's and Stone's sheep Specified Area (defined as the mapped thinhorn sheep herd range plus a 50 km buffer). The BC Forest Service policy on the use of sheep grazing in forestry states that it is important to ensure that there is no physical contact between domestic sheep and wild goats or sheep and that it may be necessary to stay out of all, or a portion, of a drainage area or to modify the timing of grazing in areas populated by wild sheep and goats. Similar management recommendations have been made by many US state agencies as well as in the scientific literature.

5.3.2. Preventing the entry of domestic sheep pathogens into wild sheep habitats is the preferred method for preventing population impacts in wild sheep.

Evidence suggests that once pneumonia-causing organisms enter a wild sheep population, there are no viable methods for treatment, and negative population effects can persist for many years and, in some cases, can lead to local extirpation of populations. To date, vaccination of domestic small ruminants has not been shown to be protective for wild sheep and cannot, therefore, be relied upon for prevention. No effective wild sheep vaccine is available. Provisions for health monitoring of domestic small ruminants prior to their uses of grazing land within thinhorn sheep ranges would be difficult to implement in Yukon and northern BC at this time due to a lack of veterinary capacity, uncertainty as to which pathogens/parasites should be included in screening (due to the multi-factorial nature of wild sheep pneumonia), uncertainty about the relative importance of various pathogens in northern Canada, and lack of agreement on cost-sharing for the program. Physical separation is the method for preventing transmission of pneumonia-causing microorganisms for which there is the most scientific support and professional opinion. Arguments against this method revolve largely around reduced access to grazing land for agriculture purposes.

5.3.3. The practice of sheep grazing in Yukon and northern BC is currently confined to a very small part of the territory thereby limiting the effects of a policy of separation to a small geographic area.

Based on the available information, the domestic small ruminant industry is small in Yukon and is concentrated in areas near urban development. The impact of agriculture restrictions from grazing lands of importance to thinhorn sheep cannot be not assessed without knowledge of planned areas for agriculture development, future policies for grazing land management, and a better understanding of movements of domestic small ruminants and wild sheep in Yukon. However, under current conditions, effects of a policy of separation would be confined to a small geographic location and a small number of agriculture producers. Introduction of disease to thinhorn sheep could have a more widespread geographic effect (over space and time due hypothesized transmission and inter-generational persistence of effects) and could impact commercial and subsistence hunting economies. The impacts of such a policy on agriculture development is unknown, but could be minimized if joint planning of grazing policies are developed in advance of plans for agriculture expansion.

6. RECOMMENDATIONS FOR YUKON

(Note – Recommendations are provided only for Yukon as this risk analysis was produced for the Government of Yukon, which has authority only to act on recommendations for the Yukon and not for British Columbia)

6.1. REDUCING UNCERTAINTY ON DETERMINANTS OF RISK

1. Information to improve characterization of the likelihood of domestic small ruminant and thinhorn sheep co-mingling and/or range overlaps, to improve assessment of exposure risks and identify areas of higher exposure risk:
    a. Produce scientifically defensible descriptions of thinhorn sheep range including seasonal movement corridors and seasonal changes in abundance and distribution;
    b. Document and track locations of domestic small ruminant farms, grazing locations, and movement patterns, while taking into account farmer privacy; and
    c. Determine plans for expansion of domestic small ruminant agriculture and establish how geographic expansion of the industry may overlap with thinhorn sheep habitat.
2. Information to undertake a cost: benefit analysis of management implications to improve assessment on the magnitude of the risk:
    a. Produce valid estimates of the direct, indirect, and traditional economic value of thinhorn sheep and undertake scenario analyses to forecast the potential cost of a pneumonia outbreak in thinhorn sheep under different disease scenarios; and
    b. Produce valid estimates of the direct, indirect, and traditional economic value of the domestic small ruminant industry and forecast the future economic impact of different risk management scenarios.
3. Information on the nature, distribution, and prevalence of potential pneumonia-causing microorganisms to provide locally relevant information on the infectious risk factors.
    a. Wild sheep: Implement a cross-jurisdictional thinhorn sheep health surveillance plan, working in collaboration with British Columbia, Alaska, Alberta, and the Northwest Territories to share information from examination and testing of live or dead thinhorn sheep using a shared protocol for ongoing methods and testing for detection of pathogens and parasites of concern. Integrate and map diagnostic results. In the absence of sufficient effort across jurisdictions, explore mechanisms to fund periodic surveys and opportunistic sampling of thinhorn sheep in Yukon to ensure sufficient animals are examined to increase confidence in statement regarding pathogen presence and distribution.
    b. Domestic animals: Support activities to increase access of the domestic small ruminant sector to veterinary services and develop policies regarding reporting diagnoses of pathogens of concern. Explore the feasibility of adapting BC policies for screening domestic sheep for pathogens and health conditions before using grazing land in thinhorn sheep habitat.
    c. The above 2 recommendations would increase the knowledge of the presence of specific pathogens if sufficient resources can be assigned to create scientifically defensible information. There are limitations to detecting pathogens of concern in sub-clinical animals, issues regarding adequate sample size to have confidence in the underlying results and the need to dedicate efforts to ongoing surveillance

because the pathogen situation will change with the movement and introduction of animals. Given that the many large scale surveys in bighorn sheep have yet to resolve all uncertainty regarding the etiology of wild sheep pneumonia and given that the pathogens of concern are ubiquitous in domestic sheep, appropriate goals and expectations for increased surveillance or disease surveys need to be established thorough a consultative approach. There are other reasons for health monitoring in wild and domestic sheep that could warrant increased investment in surveillance in addition to a contribution to reducing uncertainty about the presence of pneumonia-causing agents.

4. Information regarding the nature, distribution, and prevalence of non-microbiological risk factors for pneumonia in wild sheep to provide locally relevant information on non-infectious risk factors to identify vulnerable sub-populations or locations.
    a. Assemble information on plans for agriculture expansion, other development in thinhorn ranges that can create new or changed stresses (ex. road development that affects predator movement, natural resource extraction affecting forage availability), increased tourism, anticipated effects of climate change on weather, habitat and species movement and other factors that can affect wild sheep susceptibility or exposure to infectious disease. Analysis of this information may benefit from adapting Sheep Pneumonia Risk Contact Tools being developed and applied in BC and the United States.

6.2. Risk reduction

1. Collaboratively develop domestic small ruminant grazing policies that prescribe locations, animal numbers/densities, health expectations, and other aspects of domestic animal use of land important to wildlife, focussed initially on thinhorn sheep habitats. This should be undertaken in advance of any expansion of ruminant agriculture and in advance of approval of communal grazing permits.
2. Encourage a unified program of risk management in British Columbia, Yukon, Alberta, and Alaska. As deficits in risk reduction in any region can potentially affect other regions, a shared approach that respects ecological rather than political boundaries is encouraged. This includes a statement on what is considered to be effective separation between domestic small ruminants and thinhorn sheep throughout their distribution.
3. Identify areas with highest probability of domestic ruminant-thinhorn contact and areas that may be identified as exclusion areas for domestic small ruminants and establish protocols to monitor interactions between domestic ruminants and thinhorn sheep.
4. Support the development and implementation of domestic ruminant health best management plans that maximize individual animal health, encourage biosecurity practices that reduce the likelihood of translocation of pathogens and parasites into and within Yukon and establish minimum standards of health required before allowing sheep to graze in important wildlife habitats.

6.3. Adaptive management

1. A Yukon or regional thinhorn sheep risk management working group reflecting the knowledge and interests of wild and domestic animals health managers and stakeholders should meet periodically to review advances in the knowledge on risk reduction for wild sheep pneumonia, changes in wild-farmed animal interactions in the region, and changes in known wild sheep pneumonia risk factors. Representative(s) of this group should be engaged in North American initiatives concerned with wild sheep disease prevention. This group should be tasked with providing regular summaries of new information to agriculture and wildlife managers to inform review or changes to existing programs and policies.

6.4. Research

1. There remain numerous scientific questions about the exact mechanism of disease, potential tools for disease prevention and optimal means for risk avoidance. The Government of Yukon should collaborate with the governments of British Columbia, Alberta, Northwest Territories, and Alaska to identify regional research needs and to create a mechanism to share information generated from thinhorn sheep research in their respective jurisdictions. A research strategy that takes into account research capacities and partnerships, key uncertainties limiting evidence-based management decisions, and emerging questions should be developed and reviewed on a 3-5 years basis. This strategy should be shared with researchers and funding agencies to help advocate for investment in research relevant to thinhorn sheep risk managers.
2. There is evidence that species outside of the scope of this risk analysis, such as large ruminants and camelids, may play a role in wild sheep pneumonia outbreaks. A review of literature and experience in other jurisdictions would inform the need for the Yukon to consider these species in risk reduction strategies.

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APPENDIX A: LIST OF INFECTIOUS AGENTS THAT CAN CAUSE PNEUMONIA IN DOMESTIC AND WILD SHEEP.

Pathogen	**Detected in North America in:**				**Evidence of transmission between domestic and wild sheep**	**Identified in wild sheep die-offs**
	Domestic sheep	**Bighorn**	**Dall's sheep**	**Stone's sheep**		
Bacteria						
Bibersteinia trehalosi (*Pasteurella*)	Yes Griffin et al 2010; Tomassini et al 2009; George et al 2008; Kelley et al 2005; Miller et al 2011	Yes Besser et al 2012, 2013; Dassanayake et al 2013; Rudolph et al 2007; Tomassini et al 2009; George et al 2008; Miller et al 2011)	Yes Kelley et al 2005; Jaworski et al 1998			Yes Rudolph et al 2007; George et al 2008
Arcanobacterium pyogenes	Yes Jost and Billington 2005	Yes Aune et al 1998; Potts 1938; Queen et al 1994	Yes Jenkins et al 2000			Yes Rudolph et al 2007; Aune et al 1998; Potts 1938
Bordetella parapertussis	Yes Cullinane et al 1987					
Chlamydia sp.	Yes Fukushi et al 1992	Yes Clark et al 1993				
Histophilus somni	Yes Ward et al 2006	Yes Ward et al 2006				
Klebsiella pneumonia	Yes	Yes				

Pathogen	Detected in North America in:				Evidence of transmission between domestic and wild sheep	Identified in wild sheep die-offs
	Domestic sheep	Bighorn	Dall's sheep	Stone's sheep		
		DeForge et al 1997				
Mannheimia (Pasteurella) haemolytica	Yes Griffin et al 2010; Gilmour et al 1979; George et al 2008; Foreyt et al 1994; Lawrence et al 2010; Onderka et al 1988; Queen et al 1994; Tomassini et al 2009; Kelley et al 2005; Miller et al 2011	Yes Besser et al 2013; Miller 2001; Foreyt 1989, 1994, 1996b; George et al 2008; Dunbar et al 1990; Lawrence et al 2010; Rudolph et al 2007; Onderka et al 1988; Queen et al 1994 : Tomassini et al 2009; Miller et al 2011; McKinney et al 2006	Yes Jenkins et al 2000; Black et al 1988; Foreyt et al 1996; Kelley et al 2005; Jaworski et al 1998		Yes George et al 2008; Black et al 1988; Lawrence et al 2010; Wehausen et al 2011 Bighhorn YES Bighorn to bighorn Foreyt et al 1994	Yes Aune et al 1998; Rudolph et al 2007; George et al 2008
Mycoplasma sp (ie. arginine, agalactiae, mycoides)	Yes Nicolas 2002	Yes Jansen et al 2006				
Mycoplasma ovipneumoniae	Yes Gilmour et al 1979; Besser et al 2014; Ziegler et al 2014	Yes Besser et al 2012, 2008, 2014; Rudolph et al 2007; Wolfe et al. 2010;	Yes Black et al 1988		Yes Besser et al 2012; Miller; Monello et al 2001) bighorn to bighorn Besser et al 2014 and domestic to bighorn Besser et al 2014 (lab expts)	Yes Rudolph et al 2007; Besser et al 2012
Pasteurella multocida	Yes Griffin et al 2010	Yes Besser et al 2012, 2013; George et al 2008; Queen et al 1994; Jaworski et al,	No Jaworski et al 1998		Yes George et al 2008	Yes Aune et al 1998; Rudolph et al 2007; George et al 2008

Pathogen	Detected in North America in:				Evidence of transmission between domestic and wild sheep	Identified in wild sheep die-offs
	Domestic sheep	**Bighorn**	**Dall's sheep**	**Stone's sheep**		
		1998; Miller et al 2011; McKinney et al 2006				
Pseudomonas aeruginosa; *Pseudomonas fluorescens*	Yes George et al 2008	Yes George et al 2008; Queens et al 1994				No Rudolph et al 2010
Staphylococcus aureus	Yes Queen et al 1994	No Queen et al 1994				
Streptococcus zooepidemicus, *Streptococcus* spp.	Yes Queen et al 1994; Stevenson 1974	Yes Queen et al 1994				
Parasites						
Dictyocaulus filaria	Yes Miller et al 2011	Yes Miller et al 2011				
Muellerius capillaris	Yes Pencheva & Alexandrov 2010	Yes Foreyt et al, 2009; Pybus and Shave 1984				No Miller et al 2012; 2011
Parelaphostrongylus odocoilei	No Jenkins et al 2005	No Jenkins et al 2005b	Yes Jenkins et al 2000, 2005,2005b, 2007;	Yes Jenkins et al 2005, 2005b, 2007		Yes Jenkins et al 2005; Lankester, 2001

Pathogen	Detected in North America in:				Evidence of transmission between domestic and wild sheep	Identified in wild sheep die-offs
	Domestic sheep	Bighorn	Dall's sheep	Stone's sheep		
		Yes Huby-Chilton et al 2006	Kutz et al 2001; Jenkins et al 2005			
Protostrongylus sp (ie. frosti, rufescens, stilesi)	Yes Pencheva & Alexandrov 2010	Yes Forrester 1971; Bunch et al 1999 Festa-Bianchet 1991;George et al 2008; Kutz et al 2004; Uhazy et al 1972	Yes P. stilesi Jenkins et al 2007; refs in Kutz et al 2004	Yes Kutz et al 2004		Yes Aune et al 1998; George et al 2008
Viruses						
Adenovirus	Yes Barbezange et al 2000; Cutlip et al 1996	Yes Woods 2001				
Bluetongue virus	Yes	Yes Clark et al 1993, McKinney et al 2006; Noon et al 2002; Parks et al 1974 No Clark et al 1993b	No Foreyt et al 1993			No Miller et al 2012; Clark et al 1993,1993b; Parks et al 1974; McKinley et al 2006; Noon et al 2002

Pathogen	Detected in North America in:				Evidence of transmission between domestic and wild sheep	Identified in wild sheep die-offs
	Domestic sheep	**Bighorn**	**Dall's sheep**	**Stone's sheep**		
Bovine Respiratory syncytial virus	Yes Miller et al 2011	Yes Rudolph et al 2007; Aune et al 1998 No McKinney et al 2006; Noon et al 2002; Miller et al 2011; Clark et al 1993				Yes Miller et al 2012: Rudolph et al 2007; Aune et al 1998 No McKinney et al 2006; Noon et al 2002
Corona virus	Yes			Yes (but did not cause pneumonia, clinical signs were hemorrhagic diarrhea) Jenkins et al, 2005		
Epizoonotic hemorrhagic disease virus	Yes Thompson et al 1988	Yes McKinney et al 2006; Noon et al 2002) No Schwantje 1983				No Miller et al 2012; Clark et al 1993,1993b; McKinney et al 2006; Noon et al 2002
Infectious bovine rhinotracheitis virus	No Miller et al 2011	Yes Rudolph et al 2007; Miller et al 2011	No Foreyt et al 1993			Yes Miller et al 2012: Aune et al 1998; Rudolph et al 2007
Ovine progressive pneumonia virus	Yes	No Rudolph et al 2007	No Foreyt et al 1993			No

Pathogen	Detected in North America in:				Evidence of transmission between domestic and wild sheep	Identified in wild sheep die-offs
	Domestic sheep	Bighorn	Dall's sheep	Stone's sheep		
	Deng et al 1986; Cutlip et al 1998					Miller et al 2012: Clark et al 1993, 1993b; Rudolph et al 2007
Parainfluenza-3	Yes Miller et al 2011; Zarnke et al 1983	Yes Aune et al 1998; Rudolph et al 2007; Miller et al 2011; Parks et al 1974; Clark et al 1993 No Schwantje 1986	Yes Foreyt et al 1993			Yes Miller et al 2012: Aune et al 1998; Rudolph et al 2007 No Miller et al 2012: Clark et al 1993, 1993b; Parks et al 1974; Schwantje 1986
Respiratory syncytial virus	Yes Elazhary et al 1984	Yes Clark et al 1993; Spraker et al 1986				No Miller et al 2012; Clark 1993, 1993b, Schwantje 1986; Dunbar et al 1985

APPENDIX B: Risk analysis methods

A literature search for peer-reviewed articles was undertaken using PubMed, Google Scholar, Science Direct, and Agricola database systems/search engines. The following terms were used: thinhorn sheep pneumonia; sheep pneumonia; sheep pneumonia risk; sheep pneumonia risk assessment; Stone's sheep; Dall's sheep; *Ovis dalli*; *O. dalli stonei*; Yukon sheep. In addition, we searched for literature, using the same search engines, on the pathogens identified in our search for pneunomia-causing pathogens in sheep. A stronger emphasis was placed on scientific literature that was published after 1980 due to both accessibility reasons and to the improvement in pathogen detection and elucidation methodologies (i.e. molecular tools) that have the potential to provide more information on the likelihood of transmission between species.

Non peer-reviewed literature, or 'grey literature', was searched using Google using the following terms: thinhorn sheep pneumonia; sheep pneumonia; sheep pneumonia risk; sheep pneumonia risk assessment; Dall's sheep; Stone's sheep; *Ovis dalli*; *Ovis dalli stonei*; thinhorn sheep distribution Yukon; Dall sheep distribution Yukon; Dall sheep distribution NWT; Dall sheep distribution BC; agriculture Yukon; sheep farming north; sheep farming Yukon; sheep hunting Yukon; wild sheep hunting Yukon; hunting value Yukon; sheep hunting economy Yukon; wild sheep ecology; thinhorn ecology Yukon; and agriculture value sheep Yukon.

Using many of the search terms described above, we also carried out specific searches of the following agency websites:

- Governemnt of Yukon
- Province of British Columbia
- National Park Service U.S. Department of the Interior
- Wild Sheep Working Group (Western Association of Fish and Wildlife Agencies)
- Statistics Canada

Specific searches of United States agency websites (Fish and Wildlife and/or Parks and Wildlife in most states) and Canadian provincial and territorial websites were made to determine control measures for pneumonia in bighorn sheep:

- States of California, Colorado, Wyoming, Oregon, Idaho, Alaska, Washington
- Provinces of British Columbia and Alberta
- Northwest Territories and Yukon

Laboratory data and case reports were requested and when provided were reviewed for information related to pneumonia in domestic or wild sheep from the following sources:

- Government of Yukon (data were provided)
- Northwest Territories Government (there are no case reports or data)
- Canadian Wildlife Health Centre database (data were provided)
- BC Ministry of Agriculture (no data were available during the time period allotted)

We also obtained additional clinical and epidemiologic information on specific pathogens and disease manifestations through the following online sources: World Organization for Animal Health (OIE) and the Merck Veterinary Manual.

Hazards to wild thinhorn sheep from domestic sheep were identified using the following criteria:

Step 1: Can the potential hazard cause pneumonia in wild or domestic sheep?

Step 2: Can the potential hazard infect or be transmitted by domestic sheep?

Step 3: Can the potential hazard produce negative impacts in wild sheep (includes thinhorn and bighorn sheep)?

Step 4: Is the potential hazard present in North America?

If the answer the first, second, or third steps was yes or uncertain AND it is present in North America, then the disease or pathogen was identified as a hazard and included in the table in Appendix A.

To supplement information found from the above sources, we conducted interviews with Yukon experts to provide additional context on animal and agriculture related policies, development plans, management approaches and tools, and perceptions of the issue and risk factors associated with pneumonia in wild sheep.