RANGES AND FORAYS OF BIGHORN SHEEP (*OVIS CANADENSIS*) IN THE THOMPSON REGION OF BRITISH COLUMBIA

by

EDYTA MARCISZ
MSc, University of Silesia, Poland, 2004
BSc, University of Silesia, Poland, 2002

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF SCIENCE
IN
ENVIRONMENTAL SCIENCE

Thompson Rivers University
Kamloops, British Columbia, Canada
April 2021

Thesis Examining Committee:

Karl Larsen (PhD), Professor and Thesis Supervisor
Department of Natural Resource Sciences, Thompson Rivers University

David Hill (PhD), Associate Professor and Thesis Supervisor
Department of Geography and Environmental Studies, Thompson Rivers University

Mila Kwiatkowska (PhD), Associate Professor and Committee Member
Associate Professor, Department of Computing Science, Thompson Rivers University

Beth MacCallum (MSc, P.Biol.), External Examiner
Bighorn Wildlife Technologies Ltd.

Gerad Hales (MSc, RPBio), Additional Member
Wildlife Management Specialist (Small Game and Birds), British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development

ABSTRACT

The movements of animals provide insight into their spatial distribution, landscape use, gene flow, and potential for diseases transmission, and thus are an important measure in the study of the species' ecology and the development of conservation plans and management practices. Species exhibiting gregarious social-structures generally conduct their movements as part of a herd, but also as individual, and so can increase their likelihood of contact with other herds or species, including domestic individuals.

This study provides an analysis of movements of Bighorn Sheep (*Ovis canadensis*) in the Thompson Region of British Columbia relative to proximity of domestic sheep (*Ovis aries*). I used GPS location data of 40 rams from four different herds monitored during 2015-2018 to evaluate home range and core areas of each ram group while providing the comparison of four home range estimation methods. Each of the bands exhibited non-migratory behaviour. The animals used the same geographic area through the year, rather than migrating across the landscape. Further, while their seasonal ranges overlapped significantly, the ranges were considerably larger during the relatively short rutting season than in other seasons. These observations match those reported in previous studies where reintroduced Bighorn Sheep herds occupied relatively small areas and often exhibited no or short migration movements.

The results of this study confirm connectivity between my focal herds and an area occupied by a herd not included in this study. Collared rams from the focal herds displayed short foray movement of less than 6 km, which contrasts with that reported elsewhere. These short forays suggest a lower level of risk of contact with domestic animals existing outside of the herd home ranges. However, it should be emphasized that despite this lower risk, the likelihood of a transmission event cannot be completely discounted. Also, significant amount of private land overlaps or lays adjacent to the home ranges of the study herds, indicating that expanded future use of these lands for livestock range and/or an increase in Bighorn Sheep populations will increase the likelihood of contact between domestic and wild sheep. Thus the risk of contact with domestic sheep is high. Overall, my findings are relevant for establishing operational rules for land use practices and activities seeking to reduce impacts on bighorn herds.

Table of Contents

List of Figures

List of Tables

ACKNOWLEDGMENT

I thank my thesis supervisor, Dr. Karl Larsen, for accepting me as a student and for all of the opportunities he has given me. I could not have completed this research without his constant patience, guidance, wisdom and support. His tremendous dedication to the students is an invaluable asset for Thompson Rivers University. I would also like to give special thanks to my co- supervisor, Dr. David Hill, for his willingness to help and all of his guidance throughout the analysis process. I would also like to thank to my third committee member Dr. Mila Kwiatkowska for her assistance, and to my external examiner, Beth MacCallum, for her time and insight through the editorial and defense process.

I thank the BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD) for providing me with such an interesting and meaningful project. Special thanks goes out to Gerad Hales, Wildlife Management Specialist (Small Game and Birds), Chris Procter, and Francis Iredale, Wildlife Biologists from the Ministry, their insightful comments were invaluable. Thanks to Jeremy Ayotte for his suggestions and assistance with my foray data analysis.

This project wouldn't have been possible without funding from the Habitat Conservation Trust Foundation (HCTF) and Forest Enhancement Society of British Columbia (FESBC). Thank you.

I would also like to thank Chilcotin Holidays and Wilderness Stewardship Foundation for providing me with the opportunity to learn about wildlife, the need of its conservation, and inspiration to peruse it as my life path.

Finally, I would like to thank my family and friends for their support and for believing in me during this belated endeavor to pursue my passions. Going back to school after all these years was rather ambitious and I am grateful for their encouragement, patience, and confidence in me throughout this experience. Special mention goes out to Kristin Noack, for allowing me to express excitement, frustrations, triumphs and losses, freely and frequently with words of encouragement despite being half the world away from me. I would like to

acknowledge all of my lab-mates, especially Susan Dulc and Shannon Mendt for encouraging me to attend fitness bootcamps, and for providing feedback throughout my time at TRU.

Thank you for the countless memories!

You cannot share your life with a dog or a cat and not know perfectly well that animals have personalities and minds and feelings.

- Jane Goodall

Chapter One: Introduction

Herding animals: together or separate

Animals that move in a collective fashion with conspecifics have long attracted attention, both by hunters, the general public, and researchers (Herbert-Read 2016; Hughey et al. 2017; Parrish and Edelstein-Keshet 1999). Herding, flocking, communal denning and roosting, lekking and schooling are all examples of aggregations of animals, and these behaviors exist in a wide range of taxa (McDowall and Lynch 2019; Morrell and James 2008; Herbert-Read 2016; Cote et al. 2017). The term 'herding' has been applied largely to mammals, and in particular grazing ungulates (but see Parrish and Edelstein-Keshet 1999; McDowall and Lynch 2019). Herding occurs when a group of individuals demonstrate similar and/or cohesive behaviour: it does not occur as a result of planning or coordination. As a benefit, herding reduces the risk of predation (Pays *et al.* 2012), allows herd members to exchange information about food resources such as their location (Couzin and Krause 2003; Danchin *et al.* 2004), contributes to greater foraging success (Macdonald 1983), and facilitates energy conservation during harsh weather (Portugal *et al.* 2014). However, living with a herd carries disadvantages, such as greater competition for food (Jakob 2004) and reproduction (Boyko *et al.* 2004), a higher risk of disease transmission (Thompson and Lendrem 1985), and a higher aggression rate between conspecifics (Hoogland 1979). Some of these factors increase the probability of group fission by generating 'conflicts of interest' (Conradt and Roper 2005; Ruckstuhl 2007; Sueur *et al.* 2011). When a conflict of interest appears (for example, when reproductive competition is too high), it may be more advantageous for individuals to separate from the herd, although this requires surrendering the safety of being in a group (Conradt and Roper 2005). But to exist, behaviour leading to the separation of individuals from a herd must be viewed as an adaptive outcome of natural selection (Darwin 1871).

The separation of individuals from herds may be permanent or temporary. Dispersal occurs at a larger spatial scale and is limited in time to movements between successive breeding locations (i.e. breeding dispersal), or from the natal site to the first breeding site (i.e. natal dispersal). Another motivation to separate from the group is dispersal as a prerequisite for range expansion (Colbert *et al.* 2001) or connectivity between herds that contributes to increased reproductive success (Ciuti 2011). Sex-biased differences in juvenile dispersal are common and for mammals it is most often young males that are the predominant disperser (Greenwood 1980). In a polygynous mating system, males will have higher reproductive success if they secure a territory and/or gain dominance (Ciuti 2011). Thus, to avoid sexual competition with older and more powerful males, juvenile males often will favor emigration (Lawson and Perrin 2007). While dispersal usually takes place at or prior to reproduction, migration occurs seasonally between discrete habitats and involves all or a large part of the population.

In ungulates, migration (elevational and latitudinal) is particularly common and round-trip migration distances may vary from short excursions to trips up to thousands of kilometers, allowing the animals to access resources that seasonally change across the landscape (Berger 2004; Harris *et al.* 2009). The spatial and temporal structure of migration movements are based on evolutionarily-successful behavioural decisions in response to numerous physical, biological and environmental stimuli (Patterson *et al.* 2008; Sims 2010). Generally, migratory populations support higher numbers and demographic rates than resident, non-migratory populations (Albon and Langvatn 1992; Hebblewhite and Merrill 2011). Migratory species balance energetic costs against nutritional benefits by timing their seasonal movements across elevational and latitudinal landscapes (Pettorelli *et al.* 2007, Sawyer and Kauffman 2011, Bischof *et al.* 2012). In addition, the spatial scale at which resource change may require different migration distances. Mueller *et al.* (2011) found that migratory species occupied areas that varied on a broad scale with repeated annual pattern, while resident species occupied areas with more variation at fine scale. As the fine-scale resource variability increases, the distance an animal would need to move to reach an area with different resource availability decreases, possibly leading to shorter migration distances or even non-migratory behaviour (van Moorter *et al.* 2013). Shorter exploratory movements for foraging opportunities or finding mates may be termed forays.

Forays (exploratory movements) are similar to dispersal movements in terms of timing and distance travelled, but the animals return to their starting locality. Forays are important precursors for ecological processes such as gene flow (Suter *et al.* 2007; Dugdale *et al.* 2007) and dispersal (Young and Monfort 2009), and are common in vertebrates including fish (Bartels 1984), birds (Naguib *et al.* 2001; Norris *et al.* 2001; Williams *et al.* 2005), and mammals (Woodroffe *et al.* 1995; Teichroeb *et al.* 2011; Debeffe *et al.* 2014). There are three types of foray movements: (1) to seek extra-pair copulations, usually limited to the reproductive season (White *et al.* 2000; Iossa *et al.* 2008; Debeffe *et al.* 2014); (2) to gain information about dispersal opportunities, usually by subordinate individuals to gain experience (Messier 1985; Kesler *et al.* 2007; Debeffe *et al.* 2013); and (3) to increase foraging success. Foray movements also are usually skewed towards males. For example, in a study on gray fox (*Urocyon cinereoargenteus*) 68% of foray movements were conducted by males and 32% by females (Deuel *et al.* 2017). One important, negative consequence of forays is that they may increase the likelihood of disease transmission between herds or even species. One striking example of this is the transmission of disease between herds of Bighorn Sheep (*Ovis canadensis*) and closely-related domestic animals.

STUDY SPECIES

Bighorn Sheep are an iconic herding ungulate that occurs throughout western North America in a naturally fragmented distribution, with herds and larger population centers associated primarily with rugged, mountainous terrain (Bleich *et al.* 1997). Buechner (1960) estimated 1.5-2 million Bighorn Sheep existed at the beginning of the 19th century, but overharvest and the introduction of non-native respiratory pathogens from domestic livestock reduced them to only 15,000-18,200 by 1960. Adapted to exploit climax grassland communities, Bighorn Sheep are habitat specialists. They have blocky-bodies with short legs that are poorly adapted for retreat across flat terrain or through deep snow (Geist 1971). They use both anthropogenic and natural grasslands that offer abundant forage, and typically use habitats restricted to within 400–500 m of steep, rocky escape terrain with open visibility

Fig. 1. 1: Bighorn Sheep (*Ovis canadensis*) in characteristic steep, rocky terrain with open visibility. Photo by author.

(Demarchi *et al.* 2000) (Fig. 1.1). Restoration efforts since 1950s have resulted in modest increases in abundance and distribution; still, Bighorn Sheep occupy a small fraction of their historical range (Fig. 1.2) with varied migratory behaviors from resident to long-distant migrants (DeCesare and Pletscher 2006; Sawyer *et al.* 2016; Courtemanch *et al.* 2017). Recent studies across restored and native populations of Bighorn Sheep suggest that migration routes between seasonal ranges likely are culturally transmitted and socially taught (Jesmer *et al.* 2018, Lowrey *et al.* 2019). This difference is especially visible between restored and native populations. Restored groups, translocated into unknown landscape, are less migratory than native ones who maintain a continuous presence on the landscape, thus developing long- term population "knowledge" of the area. The understanding of how and why animals move (including forays) and migrate is essential to the effective management and restoration of wild animal populations.

Like many ungulates, Bighorn Sheep form spatially structured, sexually-segregated groups within herds, and remain in these groups during most of the year (Geist 1971; Festa-Bianchet 1991; Ruckstuhl 1998). Groups of individuals that interact often and share part of a common home range throughout most of the year are considered the basic demographic and genetic units of bighorn populations (Geist 1971; Rubin *et al.* 1998; Boyce *et al.* 1999). Population connectivity for bighorns thus is highly dependent on the movement of individuals among and between these groups. Exploratory movements (forays) of males, particularly during the rut, generally is to be one mechanism to connect populations (Geist 1971, Bleich *et al.* 1997, Boyce *et al.* 1997, Rubin *et al.* 1998). The timing and extent of this movement is variable and increases the likelihood to vector disease.

Since the mid-1800s reports of large-scale Bighorn Sheep die-offs have been documented (Martin *et al.* 1996; Toweill and Geist 1999). As Bighorn Sheep are susceptible to a variety of pathogens transferred from domestic sheep, including *Mycoplasma ovipneumoniae* (often referred to as '*M.ovi*') and *Mannheimia haemolytica*, they significantly contributed to historical declines and extirpations of the species (Cassier *et al.* 2017). Many experiments have been conducted to provide the evidence of containing those pathogens from domestic livestock like sheep (*Ovis aries*), goats (*Capra aegagrus*), and llamas (*Lama glama*) (Onderka and Wishart

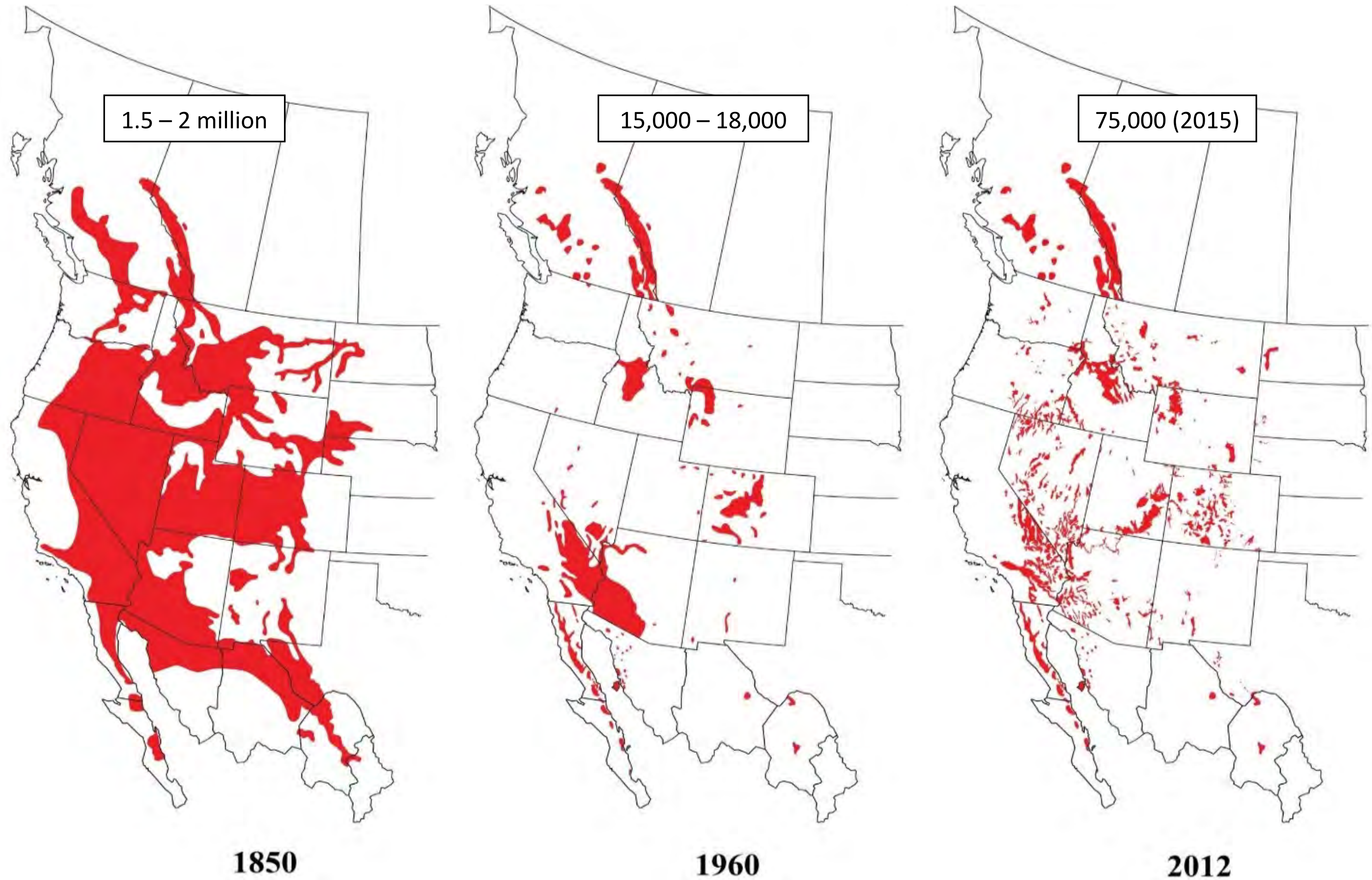

Fig. 1. 2: Historical distribution of Bighorn Sheep in North America (WAFWA, 2020)

1984; Edwards *et al.* 2010; Besser *et al.* 2012). Once pneumonia pathogens are introduced to a population of Bighorn Sheep, initial all-age mortality can exceed 80% followed by poor lamb survival for several decades (Enk *et al.* 2001; Montana Fish, Wildlife and Parks 2010). Bighorn rams often are the focus of such study, given their greater tendency to make forays (Singer *et al.* 2000; DeCesare and Pletscher 2006; O'Brien *et al.* 2014), disperse as juveniles, and interact with domestic livestock (especially sheep, but also goats or llamas) or other infected herds (Onderka and Wishart 1984; George *et al.* 2008; Besser *et al.* 2012). Poor range condition (e.g. overgrazing, weeds), mineral deficiencies (e.g. selenium) or weather (e.g. drought, severe winter) are other environmental stresses that affect Bighorn Sheep health, but contact with domestic sheep remains the highest priority issue for all wild sheep management agencies in North America (Western Association of Fish and Wildlife Agencies (WAFWA) 2014).

The distribution of Bighorn Sheep in British Columbia, Canada, is complicated, as is the implication for disease transfer. Historically there were likely two large metapopulations of Bighorn Sheep in the province of British Columbia (BC) (Fig. 1.1.), those associated with central and southern BC and those associated with the Rocky Mountains. Habitat fragmentation, loss of former grasslands to development, and conifer invasion has fragmented the central and southern Bighorn Sheep into four separate metapopulations: Fraser River, Thompson River, Okanagan-Similkameen, and Kettle-Granby River (Demarchi et. al. 2000). Within these, there are 59 herds currently recognized within 24 subpopulations: 10 of the "California" form and 14 of the "Rocky Mountain" form (Demarchi 2002). Bighorn Sheep are on the provincial Blue List in British Columbia (BC Conservation Data Centre 2021). This listing officially recognizes that the species is of Special Concern (formerly Vulnerable) and could become threatened or endangered if proper conservation measures are not followed.

California Bighorn Sheep were successfully reintroduced to the Thompson Region on the north side of Kamloops Lake (50°45'N 120°40'W) in the 1960s, and into the Kettle-Granby watershed in the 1980s, while Rocky Mountain bighorns were introduced in the Spences Bridge and Squilax (Chase) area in the 1920s (BC Ministry of Water Land and Air Protection 2004). Within this area the California form generally occurs between 300 to 2800 msl, whereas the Rocky Mountain form generally occurs between 500 and 3000 msl (although the animals can be found as low as 175 msl at an introduction site at Spences Bridge (BC Ministry of Water Land and Air Protection 2004). Within the Thompson Region there are an estimated 1,900-2,100 Bighorn Sheep (BC FLNRORD unpubl. 2018), an increase from a previous 2012 estimate of approximately 1,540 animals (Kuzyk et al. 2012).

Disease outbreaks have impacted Bighorn Sheep in the Thompson watershed and nearby areas. In the late 1990s and early 2000s, there were large declines (75%) due to a large die-off in the Okanagan, in the Fraser Basin declines were up to 50% with long-term low lamb survival and continued decline (BC Ministry of Water Land and Air Protection 2004). The most recent outbreak in British Columbia, confirmed to be *M.ovi* related, occurred near Clinton in 2013 with a loss of 80% of the herd. Recognizing that both wild and domestic sheep conduct long forays, guidelines for vegetation management in British Columbia recommend a minimum of 15km separation or significant geographical barriers between free ranging domestic and wild sheep (Schwantje 1992; Porter and Sandborn 2014; Poole and Ayotte 2019).

Thesis Objectives

This thesis addresses the movement patterns and their potential consequences of four Bighorn Sheep herds in the Thompson Region within the Interior of British Columbia, Canada. The recent sudden decline of the herd near the town of Clinton (‘Chasm herd’) raised concerns of infection spreading to nearby herds constituting the core of the Bighorn Sheep populations in the Thompson Region. To this end the BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD) initiated a GPS collaring project that monitored 40 rams during 2015-2018. As only rams were collared I use their collective movements as representative of the respective herds, and I use the term “band” when referring to the results of my data analysis, and “herd” when generalizing to the larger knowledge base on Bighorn Sheep.

The goals of this project are three-fold:

(1) improve knowledge on contact (realized and potential) between herds of Bighorn Sheep in the area,

(2) evaluate the risk of contact between bighorn and domestic sheep, and

(3) develop a herd health baseline dataset from samples from individuals in each herd (this goal was achieved by biologists during the capturing and collaring phases).

Using the GPS location data obtained on these animals, I pursued the following specific objectives for my thesis:

- evaluate home range and core size of Bighorn Sheep rams, while providing a comparison and assessment of four estimation methods,
- define migration timing and movement rates between seasonal ranges,
- quantify connectivity of the selected Thompson Bighorn Sheep,
- create a model of Bighorn Sheep habitat suitability for the Thompson Region (source habitats assessment),
- define rate and distribution of foray movements,
- model the risks of contact between Bighorn Sheep and domestic sheep based on source habitat model.

To achieve these objectives, this thesis is divided into two main research chapters and a concluding chapter. Chapter 2 addresses the migratory movements (elevational and latitudinal) of the studied animals and the delineation of their ranges (including seasonal ones). In Chapter 3, I focus on individual ram forays and evaluate the probability of contact between domestic and wild sheep, i.e. the risk of disease vectoring. In my concluding chapter (Chapter 4) I broadly summarize the results of the study, draw final conclusions and provide recommendations for future research and monitoring that will contribute to our understanding and conservation of Bighorn Sheep in this area.

STUDY SITE

For this thesis I studied four Bighorn Sheep herds in the Thompson Region within the Interior of British Columbia, Canada, located on both sides of the Thompson River, and Kamloops Lake west to Kamloops, BC (50°40’34”N 120°20’27”W, 345 m above mean sea level, amsl thereafter, Fig. 1.3). The TransCanada Highway (No. 1), local roads, agricultural and residential areas, as well as Indian Bands Reserves occur within or in proximity to these herds. A variety of recreational activities occur in the area including hiking, bicycling, horseback riding, bird watching, and hunting. Other stakeholders and land use activities with the potential to impact the herds occur within the region.

The study area occurs in the Southern Interior Ecoprovince and Semi-Arid Steppe Highland Ecodivision, characterized by warm to hot summers and cold winters (D. A. Demarchi 2011). Elevation across the study area ranges from approximately 127 amsl to 2,956 amsl. The southern slopes along lakes and rivers often are windswept and in combination with solar radiation can be free of snow throughout the winter. Habitat here generally consists of large expanses of southerly and westerly-facing grassland slopes dominated by sagebrush (*Artemisia tridentata*) and bunchgrass (*Agropyron spicatum, Festuca scabrella, Festuca idahoensis, Elymus cinereus*). Disturbed areas typically are dominated by invasive species and noxious weeds, such as cheatgrass (*Bromus tectorum*), bulbous bluegrass (*Poa bulbosa*), Kentucky bluegrass (*Poa pratensis*), and knapweed species (*Centaurea spp.*). Open forested areas are dominated by Ponderosa pine (*Pinus ponderosa*) and Interior Douglas-fir (*Pseudotsuga menziezii*). The landscape also is characterized by terraces, benches, and rugged valley walls associated with the U-shaped valley of the Thompson River system. The terrain is interposed with silt cliffs, rock faces, and talus slopes that provide escape terrain for the Bighorn Sheep (Fig. 1.4).

Average mean daily temperatures at the Kamloops airport for the 30-year mean (1990-2020) were -4.8^{o}C and 20.8^{o}C for January and July, respectively (Climate Canada 2020); while for the study years (2015-2018) were -2.2 ^{o}C for January and 22.3 ^{o}C for July (Climate Canada 2020). The lowest precipitation occurs in March with an average of 13 mm, followed by the largest amounts in June (average 34 mm, Fig. 1.5, Climate Canada 2020).

Potential predators of Bighorn Sheep in the study area include Black Bear (*Ursus americanus*), Cougar (*Puma concolor*), Wolf (*Canis lupus*), Coyote (*Canis latrans*), and Golden Eagle (*Aquila chrysaetos*) (Demarchi *et al.* 2000). The study area also supports a high density of Mule Deer (*Odocoileus heminous*) that may compete for winter range (Johnson *et al.* 2013).

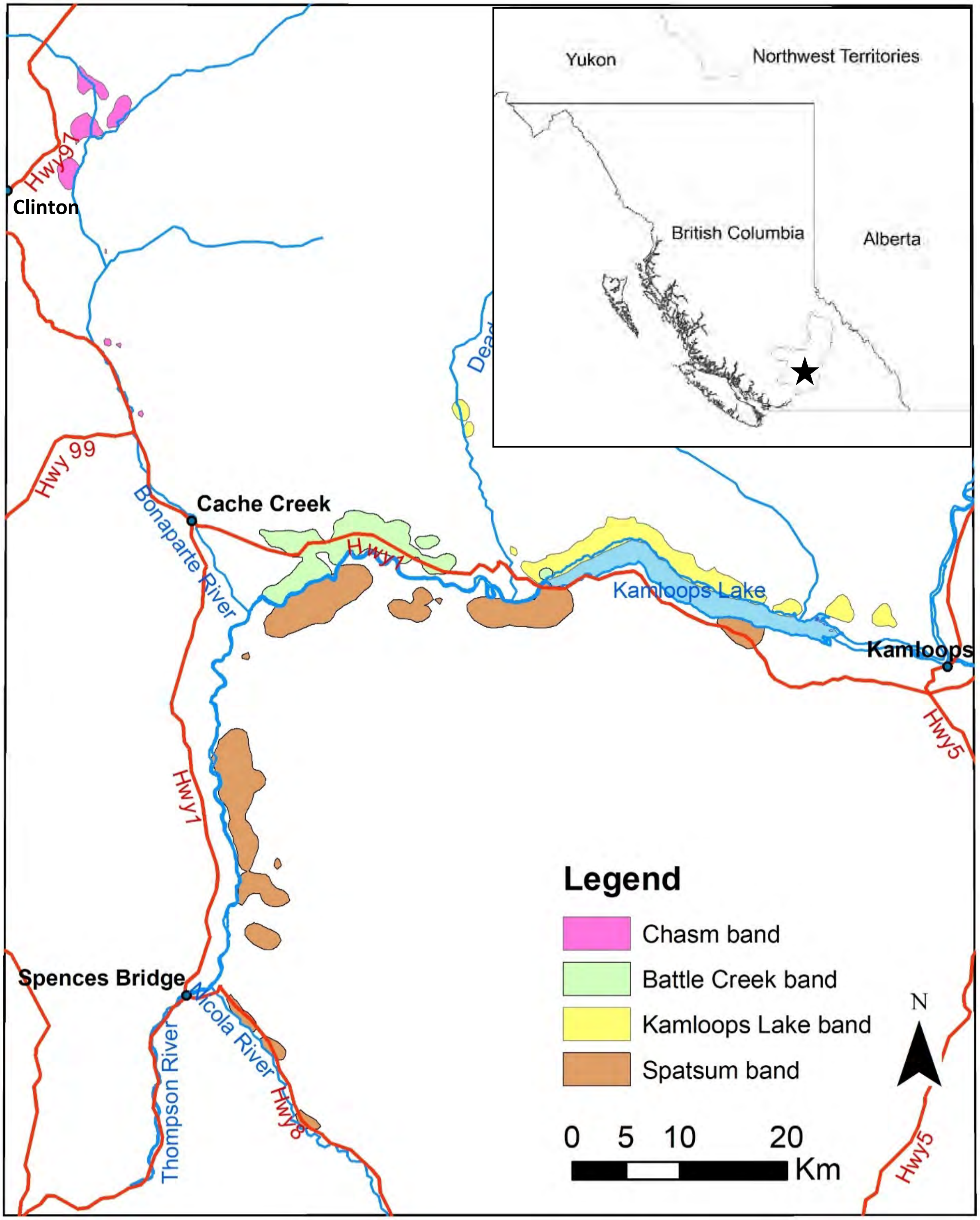

Fig. 1. 3: Location of study area of four Bighorn Sheep (*Ovis canadensis*) bands within the Thompson Region of the southern Interior of British Columbia, Canada (95% KDE, based on data collected from 2015 to 2018).

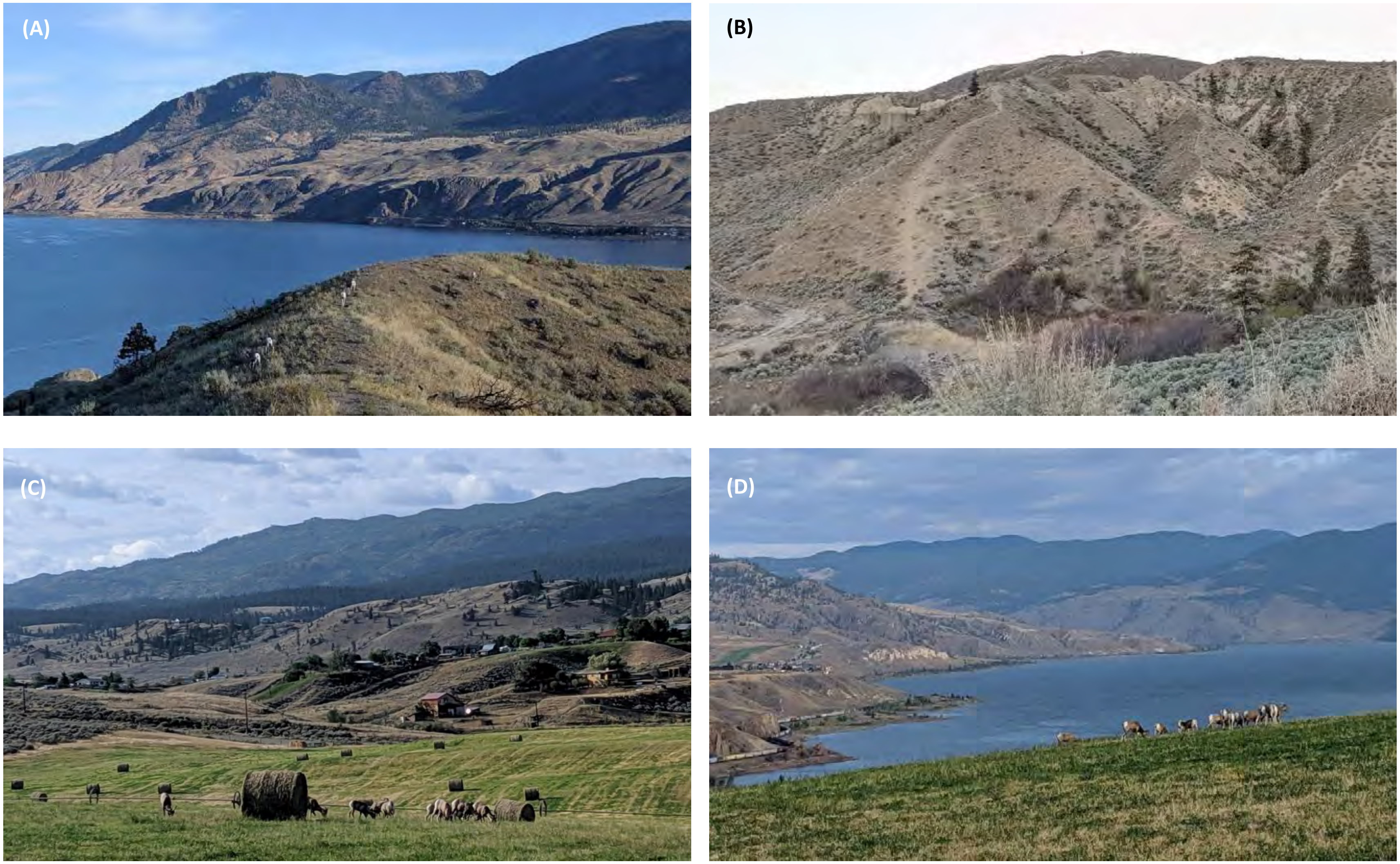

Fig. 1. 4: Characteristic habitat occupied by Bighorn Sheep (*Ovis canadensis*) in Thompson Region, British Columbia, Canada: (A) grasslands with mid-elevation rocky slopes, (B) sagebrush (*Artemisia tridentata*) and bunchgrass (*Agropyron spicatum, Festuca scabrella, Festuca idahoensis, Elymus cinereus*), (C) parkland forest with Ponderosa Pine (*Pinus ponderosa*) and Douglas-Fir (*Pseudotsuga menziezii*) and agriculture areas, and (D) canyons, and deep valleys walls of the Thompson and Nicola Rivers. Photos by author.

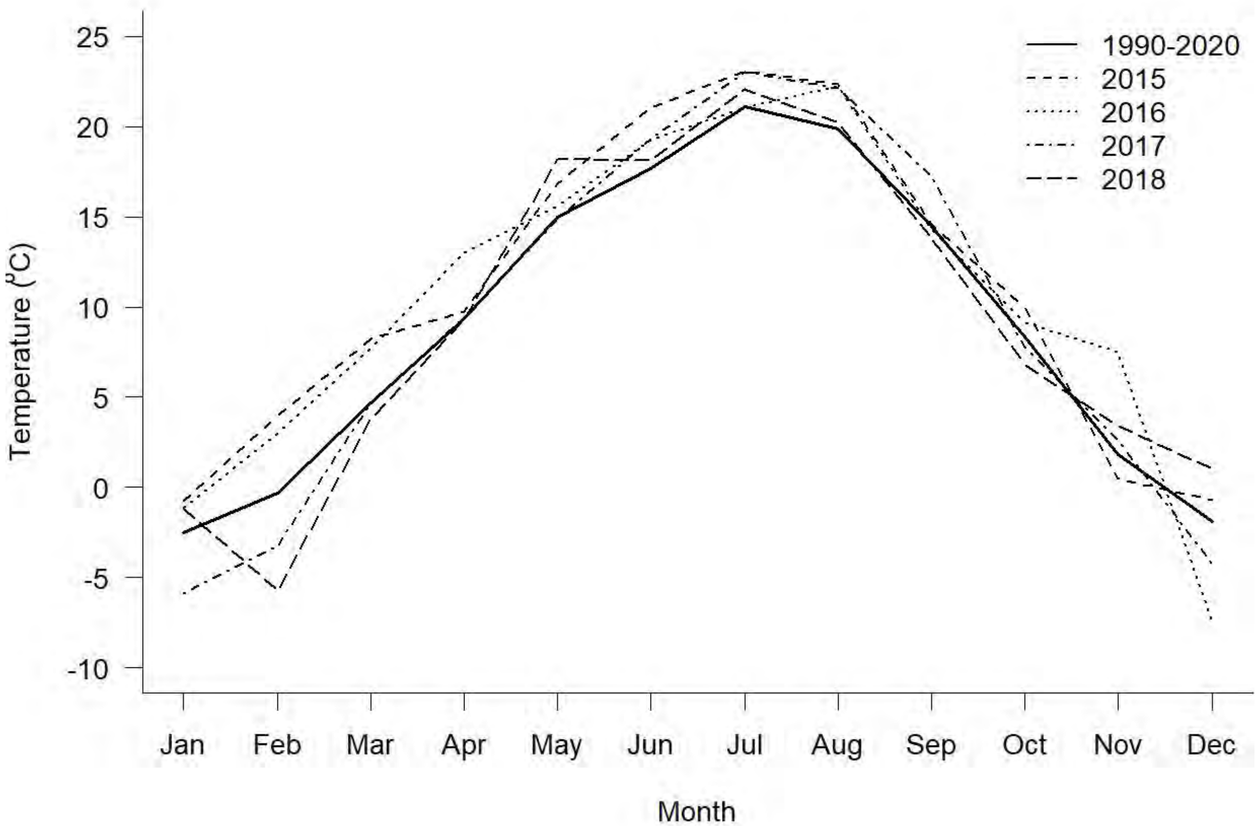

Fig. 1. 5: Mean monthly temperature (°C) in the Thompson Region during the study years (2015-2018) compared to the 30-year mean (1990-2020). Data recorded at the Kamloops Airport, British Columbia, Canada (Environment and Climate Change Canada 2020).

Literature Cited

Albon, S. D., and R. Langvatn. 1992. Plant phenology and the benefits of migration in a temperate ungulate. Oikos, 65:502–513.

Bartels, P. J. 1984. Extra-territorial movements of a perennially territorial damselfish, *Eupomacentrus dorsopunicans Poey*. Behaviour 91, 312–321.

BC Conservation Data Centre. 2015. Conservation status report on Bighorn Sheep. Ferguson 2004: 1–10. https://a100.gov.bc.ca/pub/eswp/esr.do?id=16396

BC Conservation Data Centre. 2021. https://www2.gov.bc.ca/gov/content/environment/plants-animals-ecosystems/conservation- data-centre/explore-cdc-data/glossary-for-species-ecosystems-at-risk. Accessed 29 May 2021.

BC Ministry of Water Land and Air Protection. 2004. Bighorn Sheep (*Ovis canadensis*) in accounts and measures for managing identified wildlife. Accounts V. 2004. http://www.env.gov.bc.ca/wld/frpa/iwms/documents/Mammals/m_bighornsheep.pdf

Berger J. 1978. Group size, foraging, and antipredator ploys: An analysis of Bighorn Sheep decisions. Behavioral Ecology and Sociobiology - Springer Journal. 4:91–9.

Besser, T. E., M. A. Highland, K. Baker, E. F. Cassirer, N. J. Anderson, J. M. Ramsey, K. Mansfield, D. L. Bruning, P. Wolff, J. B. Smith, and J. A. Jenks. 2012. Causes of pneumonia epizootics among Bighorn Sheep, western United States, 2008–2010. Emerging Infectious Diseases 18:406–414.

Bischof, R., L. E. Loe, E. L. Meisingset, B. Zimmerman, B. Van Moorter, and A. Mysterud. 2012. A migratory northern ungulate in the pursuit of spring: Jumping of surfing the green wave? American Naturalist 180:407–424.

Bleich, V.C., R.T. Bowyer, and J.D. Wehausen. 1997. Sexual segregation in mountain sheep: resources or predation? Wildlife Monographs 134, 1–50.

Boyce, W. M., R. R. Ramey, T. C. Rodwell, E. S. Rubin, and R. S. Singer. 1999. Population subdivision among desert Bighorn Sheep (*Ovis canadensis*) ewes revealed by mitochondrial DNA analysis. Molecular Ecology 8:99–106.

Boyko, A. R., R.M. Gibson, and J.R. Lucas. 2004. How predation risk affects the temporal dynamics of avian leks: greater sage grouse versus golden eagles. American Naturalist, 163,154-165.

Buechner, H. K. 1960. The Bighorn Sheep in the United States, its past, present, and future. Wildlife Monographs 4:1-174.

Cassier K. R. Manlove, E. S. Almberg, P. Kamath, M. Cox, P. L. Wolff, A. Roug, J. M. Shannon, R. Robinson, R. B. Harris, B. J. Gonzales, R. K. Plowright, P. J. Hudson, P. C. Cross, A. Dobson, and T. E. Besser. 2017. Pneumonia in bighorn sheep: Risk and resilience. Journal of Wildlife Management 82 (1): 32–45

Ciuti S., and M. Apollonio. 2011. Do antlers honestly advertise the phenotypic quality of fallow buck (*Dama dama*) in a lekking population? Ethology, 117:133–144.

Conradt, L., and T.J. Roper. 2005. Consensus decision making in animals. Trends in Ecology & Evolution, 20, 449-456.

Cote, J., G. Bocedi, L. Debeffe, M. E. Chudzińska, H. C. Weigang, C. Dytham, G. Gonzalez, et al. 2017. Behavioural Synchronization of Large-Scale Animal Movements – Disperse Alone, but Migrate Together? Biological Reviews 92 (3): 1275–96.

Courtemanch, A. B., M.J. Kauffman, S. Kilpatrick, and S.R. Dewey. 2017. Alternative foraging strategies enable a mountain ungulate to persist after migration loss. Ecosphere, 8, 1–16

Couzin, I.D., and J. Krause. 2003. Self-organization and collective behavior in vertebrates. Advances in the Study of Behavior, 32, 1-75.

Creel S., J. Winnie, B. Maxwell, K. Hamlin, and M. Creel. 2005. Elk alter habitat selection as an antipredator response to wolves. Ecology, 86:3387–97.

Danchin, E., L. A. Giraldeau, T.J. Valone, and R.H. Wagner. 2004. Public information: from nosy neighbors to cultural evolution. Science, 305, 487-491.

Darwin, C. 1871. The descent of man and selection in relation to sex. Murray, London, United Kingdom, 372 pp.

Debeffe, L., N. Morellet, B. Cargnelutti, B. Lourtet, A. Coulon, J.M. Gaillard, R. Bon, and A.J.M. Hewison. 2013. Exploration as a key component of natal dispersal: dispersers explore more than philopatric individuals in roe deer. Animal Behaviour 86, 143–151

Debeffe, L., S. Focardi, C. Bonenfant, A. J. M. Hewison, N. Morellet, C. Vanpe, and M. Heurich. 2014. A one night stand? Reproductive excursions of female roe deer as a breeding dispersal tactic. Oecologia 176, 431–443

Deuel, N. R., M. L. Conner, K. V. Miller, M. J. Chamberlain, M. J. Cherry, and L. V. Tannenbaum. 2017. Gray fox home range, spatial overlap, mated pair interactions and extra-territorial forays in Southwestern Georgia, USA. Wildlife Biology 1 (2017): wlb.00326.

DeCesare, N. J., and D.H. Pletscher. 2006. Movements, connectivity, and resource selection of Rocky Mountain Bighorn Sheep. Journal of Mammalogy, 87, 531–538.

Demarchi, R.A., C.L. Hartwig, and D.A. Demarchi. 2000. Status of the California Bighorn Sheep in British Columbia. BC Ministry Environment, Lands and Parks, Wildlife Branch, Victoria, BC. Wildlife Bulletin No. B-98., no. March: 53 pp. https://pdfs.semanticscholar.org/ae96/a864cdf65a5ed12cf9fd4bc8b023abbdf7d6.pdf.

Demarchi, R. A. 2002. Bighorn Sheep, *Ovis canadensis*. Pages 433-454 *in* K. Paige (technical editor), Standards for managing identified wildlife, Version 2. Draft for technical review. Ministry of Water, Land and Air Protection, Biodiversity Branch, Victoria, BC. 492pp.

Dugdale, H. L., D.W. Macdonald, L.C. Pope, and T. Burke. 2007. Polygynandry, extra-group paternity and multiple-paternity litters in European badger (*Meles meles*) social groups. Molecular Ecology 16, 5294–5306.

Edwards, V. L., J. Ramsey, C. Jourdonnais, R. Vinkey, M. Thompson, N. Anderson, T. Carlsen and C. Anderson. 2010. Situational agency response to four Bighorn Sheep die-offs in western Montana. Biennial Symposium of the Northern Wild Sheep and Goat Council. 29–50. http://bighorndiseaseinfo.altervista.org/Bighorn_Disease_Documents/Situational_agency_response_to_4_bighorn_die-offs_in_Montana_NWSGC_2010.pdf

Enk, T. A., H. D. Picton, and J. S. Williams. 2001. Factors limiting a Bighorn Sheep population in Montana following a die-off. Northwest Science 75:280–291.

Festa-Bianchet, M. 1991. The social system of Bighorn Sheep - grouping patterns, kinship, and ewe dominance rank. Animal Behaviour 42:71–82.

Geist, V. 1971. Mountain sheep: a study in behavior and evolution. University of Chicago Press, Chicago, Illinois.

George, J. L., D. J. Martin, P. M. Lukacs, and M. W. Miller. 2008. Epidemic *pasteurellosis* in a Bighorn Sheep population coinciding with the appearance of a domestic sheep. Journal of Wildlife Diseases 44:388–403.

Greenwood P.J. 1980. Mating systems, philopatry and dispersal in birds and mammals. Animal Behavior, 28:1140–1162.

Harris, G., S. Thirgood, J. Hopcraft, J. Cromsight, and J. Berger. 2009. Global decline in aggregated migrations of large terrestrial mammals. Endangered Species Research, 7, 55–76.

Hebblewhite, M., and E. H. Merrill. 2011. Demo graphic balancing of migrant and resident elk in a partially migratory population through forage-predation tradeoffs. Oikos 120:1860–1870.

Herbert-Read, J. E. 2016. Understanding How Animal Groups Achieve Coordinated Movement. The Journal of Experimental Biology 219 (19): 2971–83.

Hoogland, J.L. 1979. Aggression, ectoparasitism, and other possible costs of prairie dog (*Sciuridae, Cynomys spp.*) coloniality. Behaviour, 69, 1-35.

Iossa, G., C.D. Soulsbury, P.J. Baker, and S. Harris. 2008. Body mass, territory size, and life-history tactics in a socially monogamous canid, the red fox (*Vulpes vulpes*). Journal of Mammalogy 89, 1481–1490.

Jakob, E.M. 2004. Individual decisions and group dynamics: why pholcid spiders join and leave groups. Animal Behavior, 68, 9-20

Jesmer, B. R., J.A. Merkle, R.J. Goheen, E.O. Aikens, J.L. Beck, A.B. Courtemanch, and M.J. Kauffman. 2018. Is ungulate migration culturally transmitted? Evidence of social learning from translocated animals. Science, 361, 1023–1025.

Kesler, D. C., S.M. Haig, and M. Brittingham. 2007. Territoriality, prospecting, and dispersal in cooperatively breeding Micronesian kingfishers (*Todiramphus cinnamominus reichenbachii*). The Auk 124, 381–395

Kuzyk, G., P. Dielman, B. Jex, Ch. Procter, A. Reid, H. Schwantje, I. Teske, and C. Thiesen. 2012. Population and harvest trends of Mountain Sheep and Mountain Goats in British Columbia. Biennial Symposium of the Northern Wild Sheep and Goat Council 18: 87–102.

Lawson Handley L.J., and N. Perrin. 2007. Advances in our understanding of mammalian sex-biased dispersal. Molecular Ecology, 16, 1559-1578.

Li C., Z. Jiang, L. Li, Z. Li, and H. Fang. 2012. Effects of reproductive status, social rank, sex and group size on vigilance patterns in Przewalski's gazelle. PLoS One. Public Library of Science

Lowrey, Blake, Kelly M. Proffitt, Douglas E. McWhirter, Patrick J. White, Alyson B. Courtemanch, Sarah R. Dewey, Hollie M. Miyasaki, et al. 2019. Characterizing population and individual migration patterns among native and restored Bighorn Sheep (*Ovis canadensis*). Ecology and Evolution 9 (15): 8829–39.

Macdonald, D.W. 1983. The ecology of carnivore social behaviour. Nature, 301, 379-384.

Main, M.B., and B.E. Coblentz. 1996. Sexual segregation in Rocky Mountain Mule Deer. Journal of Wildlife Management 60, 497–507.

Martin, K., T. Schommer, and V. Coggins. 1996. Literature Review regarding the compatibility of bighorns and domestic sheep. Tenth Biennial Symposium Northern Wild Sheep and Goat Council. pp 72-77

McDowall, Philip S., and Heather J. Lynch. 2019. When the 'Selfish Herd' Becomes the 'Frozen Herd': Spatial Dynamics and Population Persistence in a Colonial Seabird. Ecology 100 (10): 1–13.

Messier, F. 1985. Solitary living and extraterritorial movements of wolves in relation to social status and prey abundance. Canadian Journal of Zoology 63, 239–245.

Montana Fish, Wildlife and Parks. 2010. Montana Bighorn Sheep conservation strategy. Helena, USA. https://fwp.mt.gov/binaries/content/assets/fwp/conservation/wildlife-reports/bighorn-sheep/bighorn-sheep-conservation-strategy-2010-web.pdf.

Morrell, L. J., and R. James. 2008. Mechanisms for aggregation in animals: Rule success depends on ecological variables. Behavioral Ecology 19 (1): 193–201.

Mueller, T., K.A. Olson, G. Dressler, P. Leimgruber, T.K. Fuller, and C. Nicolson. 2011. How landscape dynamics link individual- to population-level movement patterns: a multispecies comparison of ungulate relocation data. Global Ecology Biogeogrraphy, 20, 683–694.

Naguib, M., R. Altenkamp, and B. Griessmann. 2001. Nightingales in space: song and extra-territorial forays of radio tagged song birds. Journal für Ornithologie 142, 306–312

Norris, D. R., and B.J. Stutchbury. 2001. Extraterritorial movements of a forest songbird in a fragmented landscape. Conservation Biology 15, 729–736

O'Brien, J. M., C. S. O'Brien, C. McCarthy, and T. E. Carpenter. 2014. Incorporating foray behavior into models estimating contact risk between Bighorn Sheep and areas occupied by domestic sheep. Wildlife Society Bulletin 38:321–331.

Onderka, D. K., and W. D. Wishart. 1984. A major Bighorn Sheep die-off from pneumonia in southern Alberta. Biennial Symposium of the Northern Wild Sheep and Goat Council 4:356–363.

Patterson, T.A., L. Thomas, C. Wilcox, O. Ovaskainen, and J. Matthiopoulos. 2008. State-space models of individual animal movement. Trends in Ecology & Evolution, 23, 87–94.

Parrish, J. K., and L. Edelstein-Keshet. 1999. Complexity, pattern, and evolutionary trade-offs in animal aggregation. Science 284 (5411): 99–101.

Pays, O., D. Fortin, J. Gassani, and J. Duchesne. 2012. Group dynamics and landscape features constrain the exploration of herds in fusion-fission societies: the case of European roe deer. PLoS One, 7, -34678

Pettorelli, N., F. Pelletier, A. von Hardenberg, M. Festa-Bianchet, and S.D. Cote. 2007. Early onset of vegetation growth vs. rapid green-up: impacts on juvenile mountain ungulates. Ecology 88: 381–390.

Poole, Kim G, and Jeremy Ayotte. 2019. Kootenay Region Bighorn Sheep Management Plan – Draft for Discussion. BC Ministry of Forests, Lands and Natural Resource Operations, no. April.

Porter, H., and C. Sandborn. 2014. Bighorn Sheep herd die-offs in British Columbia: The need for a Provincial Wild / Domestic Sheep Separation Strategy. Environmental Law Centre, University of Victoria, Victoria, BC, no. September: 31. http://www.elc.uvic.ca/wordpress/wp-content/uploads/2016/04/BighornSheep.pdf .

Portugal, S.J., T.Y. Hubel, J. Fritz, S. Heese, D. Trobe, and B. Voelkl. 2014. Upwash exploitation and downwash avoidance by flap phasing in ibis formation flight. Nature, 505, 399-402.

Rubin, E. S., W. M. Boyce, M. C. Jorgensen, S. G. Torres, C. L. Hayes, C. S. O'Brien, and D. A. Jessup. 1998. Distribution and abundance of Bighorn Sheep in the Peninsular Ranges, California. Wildlife Society Bulletin 26:539–551.

Ruckstuhl, K. E. 1998. Foraging behaviour and sexual segregation in Bighorn Sheep. Animal Behaviour 56:99–106.

Ruckstuhl, K. E. 2007. Sexual segregation in vertebrates: proximate and ultimate causes. Integrative and Comparative Biology, 47, 245-257.

Sawyer, H., A.D. Middleton, M.M. Hayes, M.J. Kauffman, and K.L. Monteith. 2016. The extra mile: Ungulate migration distance alters the use of seasonal range and exposure to anthropogenic risk. Ecosphere, 7, 1–11.

Sawyer, H., and M. J. Kauffman. 2011. Stopover ecology of a migratory ungulate. Journal of Animal Ecology 80:1078–1087.

Schwantje, H. 1992. Interim guidelines for the use of Domestic Sheep for vegetation management in British Columbia. BC Ministry of Environment, Victoria, B.C

Shackleton, D.M., C.C. Shank, and B.M. Wikeem. 1999. Natural history of Rocky Mountain and California Bighorn Sheep. Pages 78–138 in R. Valdez, and P.R. Krausman, eds. Mountain sheep in North America. Univ. Arizona Press, Tucson, AZ.

Sims, D.W. 2010. Tracking and analysis techniques for understanding free-ranging shark movements and behavior. Sharks and their Relatives II. Biodiversity, Adaptive Physiology, and Conservation (eds J.C. Carrier, J.A. Musick & M.R. Heithaus), pp. 351–392. CRC Press Taylor & Francis Group, Boca Raton, FL.

Singer, F. J., C.M. Papouchis, and K.K. Symonds. 2000. Translocations as a tool for restoring populations of Bighorn Sheep. Restoration Ecology, 8, 6–13.

Sueur, C., A.J. King, L. Conradt, G. Kerth, D. Lusseau, and C. Mettke-Hofmann. 2011. Collective decision-making and fission-fusion dynamics: a conceptual framework. Oikos, 120, 1608-1617.

Suter, S. M., M. Keiser, R. Feignoux, and D.R. Meyer. 2007. Reed bunting females increase fitness through extra-pair mating with genetically dissimilar males. Proceedings of the Royal Society of London B: Biological Sciences 274, 2865–2871.

Teichroeb, J. A., E.C. Wikberg, and P. Sicotte. 2011. Dispersal in male ursine colobus monkeys (*Colobus vellerosus*): influence of age, rank and contact with other groups on dispersal decisions. Behaviour 148, 765–793

Thompson, D., and D.W. Lendrem. 1985. Gulls and plovers: host vigilance, klepto-parasite success and a model of kleptoparasite detection. Animal Behavior, 33, 1318-1324.

Toweill, D. and V. Geist. 1999. The Return of Royalty. Boone and Crocket Club. Missoula Montana.

van Moorter, B., N. Bunnefeld, M. Panzacchi, C.M. Rolandsen, E.J. Solberg, and B.E. Saether. 2013. Understanding scales of movement: animals ride waves and ripples of environmental change. Journal of Animal Ecology, 82, 1–11.

Western Association of Fish and Wildlife Agencies (WAFWA). North America Bighorn Sheep Historic Distribution Map. https://wafwa.org/initiatives/wild-sheep-initiative trashed/north-american-bighorn-sheep-distribution-map-1850-1960-2012/. Accessed on 9 January 2021.

Western Association of Fish and Wildlife Agencies (WAFWA), Wildlife Health Committee. 2014. Bighorn Sheep Herd Health Monitoring Recommendations. http://www.wildsheepfoundation.org/cache/DOC23_2015-01-03WAFWAWHCBHSherd healthmonitoring_Final.pdf?20160620033824

White, P., K. Ralls, and D.B. Siniff. 2000. Nocturnal encounters between kit foxes. Journal of Mammalogy 81, 456–461

Wild Sheep Working Group. 2015. Records of wild sheep translocations: United States and Canada, 1922-present. Cheyenne, WY: Western Association of Fish and Wildlife Agencies.

Williams, D. A., and K.N. Rabenold. 2005. Male-biased dispersal, female philopatry, and routes to fitness in a social corvid. Journal of Animal Ecology 74, 150–159.

Woodroffe, R., D. Macdonald, and J. Silva. 1995. Dispersal and philopatry in the European badger (*Meles meles*). Journal of Zoology 237, 227–239.

Young, A. J. and S.L. Monfort. 2009. Stress and the costs of extra-territorial movement in a social carnivore. Biology Letters, rsbl. 2009, 0032.

CHAPTER TWO: HOME RANGE AND GROUP MOVEMENTS OF BIGHORN SHEEP (*OVIS CANADENSIS*) HERDS IN THE SOUTHERN CENTRAL INTERIOR OF BRITISH COLUMBIA, CANADA

INTRODUCTION

The factors dictating the movement patterns of animal herds are complex and emerge from the collective movement decisions made by individuals. Dynamics in herd-level movement patterns generally can be separated into three categories: residency (where individuals occupy relatively small areas and reside in home ranges during their lifetimes, also known as sedentariness), migration (where individuals regularly move between spatially distant seasonal ranges), and nomadism (where individuals move long-distances along seasonally varying routes) (Mueller and Fagan 2008). These categories can be plastic and may vary between populations of the same species (e.g. Hundertmark 2007) or within the same population at different times (Spitz *et al.* 2018). Mueller *et al.* (2011) examined individual movements and their interrelation among individuals of four species of ungulates [sedentary moose (*Alces alces*), partially-migratory guanacos (*Lama guianicoe*), and two species with extreme long-distance movements: caribou (*Rangiver tarandus granti*) and gazelle (*Procapra gutturosa*)]. They related population-level movement patterns to underlying landscape vegetation dynamics, and found that migratory species were associated with landscapes that varied on a broad scale in a predictable, annual pattern, while non-migratory species lived in landscapes with more variation (temporal and spatial) at finer scales.

Understanding the patterns and correlates of seasonal herd movements of game species also is important for management. To define the spatial extent of ungulate species, information on the timing and distance of seasonal movements is necessary for informed harvesting regulations and for habitat enhancement activities. This detailed knowledge of spatial and temporal patterns of movements allows flexible and adjustable conservation planning. Situations where ungulate populations exceed the carrying capabilities of their seasonal habitats often result in serious degradation of that habitat. Research of the movement and migratory patterns of Red Deer (*Cervus elaphus*) in the Western Carpathians in Slovakia (Kropil *et al.* 2015) showed that the populations were 57% higher than the capability of their winter home ranges (and it led to overexploitation of that habitat), thus supporting an increase in hunting quotas in those areas. Movement-management frameworks, like the one proposed by Allen and Singh (2016), provide an important link between movement ecology, wildlife management, and conservation, and highlight the potential for complementary and dynamic solutions for managing wildlife.

Herd movements of Bighorn Sheep (*Ovis canadensis*) are particularly relevant to the management of the taxa in many regions within the animal's range. Understanding the plasticity of bighorn movements and migration status has crucial implications for evaluating demographic threats. A specific concern for Sierra Nevada Bighorn Sheep (*O. c. sierrae*) management is enhanced predation risk on low-elevation winter ranges co-occupied by mule deer (*Odocoileus hemionus*) herds (although the movement data showed the different timing of the use of those ranges), which resulted in increased populations of Cougar (*Puma concolor*), the primary predator of bighorn in that region (Johnson *et al.* 2013). Other evidence suggests that herds of bighorn are more interconnected than previously thought (DeCesare and Pletscher 2006; Singer *et al.* 2000). Proximity among herds increases the risk of disease transmission that may increase mortality rates (Onderka and Wishart 1984; George *et al.* 2008; Edwards *et al.* 2010; Besser *et al.* 2012; Sells *et al.* 2015). Determining bighorn population movement patterns, within their home ranges, proximity to other populations, and identifying critical habitats and limiting factors provides the knowledge necessary to manage viable populations for both hunting and non-consumptive purposes.

Bighorn Sheep are gregarious habitat specialists that also explore their landscape despite of potential risk. Closeness to escape terrain and open areas with sparse vegetation (less than 40% vegetation cover) often are mentioned when studying bighorn movement behaviour (DeCesare and Pletscher 2006; Demarchi *et al.* 2000). Escape terrain, such as steep (greater than 40º) and rocky areas, are desirable as they impede predator attacks (Smith *et al.* 1999; Demarchi *et al.* 2000; DeCesare and Pletscher 2006). Although bighorns have a strong home range fidelity, and thus generally do not expand their range (Geist 1971; Krausman 2000), they also show a tendency to undertake exploratory movements (forays) up to 50 km from their home range (O'Brien *et al.* 2014). During these exploratory movements they may contact Domestic Sheep *(O. aries)* and in doing so, increase the risk of disease transmission. Besser *et al.* (2012) confirmed that commingling with Domestic Sheep exposes bighorns to bacterial pneumonia (*Mycoplasma ovipneumoniae*) that may result in 98% mortality.

Although the benefits of defining home range for management are well established, both the definition and delineation methods are debated (Walter *et al.* 2011; Lyons *et al.* 2013; White and Garrott 2017). The wide array of methods available for estimating home rang sizes can make it difficult to choose an appropriate one for any particular situation. To address this problem, several studies now provide comparisons of home range estimators based on geographic positioning system (GPS) collaring data (e.g. Van Beest *et al.* 2011; Walter *et al.* 2011; Dürr and Ward 2014). Further complicating the issue is the fact that home ranges also can vary significantly in size between annual and seasonal use. For example, the winter range for a Bighorn Sheep herd in Elk Valley, BC (of approx. 150 sheep) was 7.7 km^2 with an annual range of 39.7 km^2, while a nearby herd had a winter range of 27.4 km^2 and a corresponding annual range of 139.6km^2 (Poole *et al.* 2018). Conversely, in their comparative study of four ungulates, Hudson *et al.* (1975) found that bighorns showed the most localized movements and were the most specific in their environmental requirements (such as slope and rockiness of escape terrain), tending to use small areas. Whilst the research question should be the main focus when selecting the method (Fieberg and Börger 2012), an understanding of how different methods perform in a specific study situation can aid the choice of the estimation method.

Numerous herds of Bighorn Sheep occur in BC; they are blue-listed by the Ministry of Environment of British Columbia, which means they are of “special concern” (formerly Vulnerable - BC Conservation Data Centre 2021) thus the existing herds are vital to maintaining the species' persistence. They are composed of two forms: “California” and “Rocky Mountain” (Demarchi 2002). These individual populations are not continuously connected, being divided into herds that may have limited opportunities for member exchange. An abrupt decline in 2012 of one herd within the Thompson Region of the province was confirmed to be disease-related (bacterial pneumonia *Mycoplasma ovipneumoniae*), raising concerns of a spread of the infection to other herds in the Thompson Region. These concerns resulted in the BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD) initiating a study of four herds within the region in question, with the goal to better understand the connectivity between those herds, as well as to evaluate the risk posed by domestic sheep farms in the area.

My objectives for this chapter were to (1) evaluate home range and core area size of Bighorn Sheep ram bands on two temporal scales (yearly, and seasonally) whilst resolving the method of home range estimation most appropriate for the study, (2) define migration timing and movement rates, and (3) quantify connectivity of the Thompson Bighorn Sheep populations.

METHODS

Study area

The study area was located in the Thompson Region within southern part of Central Interior of British Columbia. It consisted of a 20 km-wide corridor that extended from the western outskirts of Kamloops, British Columbia (BC) (50°40′34″N 120°20′27″W, 345m above mean sea level), west along Kamloops Lake (approx. 30 km), west and then south along the Thompson River (approx. 100 km), and south-east along the Nicola River (approx. 20 km) (see Fig. 1.3 in Chapter 1). The TransCanada Highway (No. 1) bisects most of the study area. The area is semi-arid according to the Köppen-Geiger climate classification (Climate Canada 2020). The elevation range from approx. 127 m to 2,956 m. The average mean daily temperatures at Kamloops are -4.8°C and 20.8°C for January and July as the coldest and warmest months respectively (Climate Canada 2020). The lowest precipitation occurs in March with an average of 13mm, with the largest amount occurring in June with an average of 34 mm (Climate Canada 2020).

Habitat is generally comprised of a large expanses of open southerly and westerly-facing grassland slopes with sagebrush (*Artemisia tridentata*) and bunchgrasses [Bluebunch Wheat Grass (*Agropyron spicatum*), Rough Fescue (*Festuca scabrella*), Idaho Fescue (*Festuca idahoensis*), Giant Wild Rye (*Elymus cinereus*), and Needle and Thread Grass (*Stipa comata*)] parkland forest (consisting of Ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*)), canyons, and deep valleys walls of the Thompson and Fraser Rivers. Potential predators of Bighorn Sheep in the study area include Black Bear (*Ursus americanus*), Cougar (*Puma concolor*), Wolf (*Canis lupus*), Coyote (*Canis latrans*), and Golden Eagle (*Aquila chrysaetos*) (Demarchi *et al.* 2000). The study area also supports a high density of Mule Deer (*Odocoileus heminous*) that may compete for winter range (Johnson *et al.* 2013). For more details on the study area see Chapter 1.

Study species, capture, and GPS telemetry

Forty rams (17 in spring 2015, 11 in fall 2015, 12 in fall 2016) were equipped with G2110E Iridium GPS collars (Advanced Telemetry Systems 2013) and unless failure occurred, locations were collected until the end of December 2018. All animals were captured by BC government biologists from a helicopter using a combination of aerial darting and net-gunning, depending upon location and behaviour. The collared rams were distributed across four herds of bighorns within the Thompson River drainage in Thompson Region: Battle Creek (13 rams), Kamloops Lake (12 rams), Spatsum (14 rams), and Chasm (2 rams) herd (see Fig. 1.3 in Chapter 1). Locations from these animals were assumed to be representative of a group given the aggregated structure of the species (Geist 1972; Demarchi *et al.* 2000).

Collars were deployed during four multi-day capture events (March/early April 2015 = 9; end of April 2015 = 8; November 2015 = 11; November 2016 = 12). Programming recorded locations once every 4 hours (i.e. 6 times a day), and data were sent to the server after acquiring 21 locations (what would be once every 84 h when working correctly). A time chart, including the span of data collection for each ram, is presented in Appendix 1. Only rams were outfitted with GPS-enabled collars, as this segment of the population has a greater tendency to explore new areas or higher risk tolerance than female bighorn (Singer *et al.* 2000)) and thus are more likely to vector disease. Hereafter I use the collective movements of rams from within each individual herd to delineate herd movements and/or migrations.

Initial attempts to define movement seasons from the location points database failed as bighorns in my study area did not show migratory movement patterns (see Results). Instead I defined 4 movement seasons based on the literature (Demarchi *et al.* 2000; Poole *et al.* 2016) and government biologist expertise (Procter and Iredale, pers. comm., FLNRORD). Consequently, winter was defined as 1 December - 31 March (characterized by low movement rates and stable use of elevation). Spring and summer were defined as 1 April - 24 August (includes lambing, use of low elevation with greening-up vegetation, and increasing movement rates). The fall/autumn period was defined as 25 August - 24 October (this period often is recognized as pre-rut and is typically characterized by variable use of elevation and declining movement rates). Mating season (also known as 'rutting') was defined 25 October - 30 November. Seasonal data from the four years of study were pooled for each band.

On December 27, 2015, 26 out of 28 collars (12 more collars were deployed in 2016) experienced a software error requiring re-programming to transmit data more frequently (every 24h to preserve daily date stamp). This more-frequent transmissions reduced battery life for those collars. Thus, only days that contained all six scheduled recordings (every 4 h as planned) were used in the analysis (92% of data), as then I could assume the time stamp was accurate (days with less than six recordings were missing localization reading(s)). I discarded GPS location points with >10 HDOP (horizontal dilution of precision) that are believed to be unreliable (Dussault *et al.* 2001). I also removed the first week of location data (42 records) for each collared animal to avoid bias associated with erratic animal movement following the collaring event. The final week of data collection (42 records) also was omitted to avoid errors caused by battery fatigue (Clapp *et al.* 2014). After all cleaning data steps 92% of the original data remained for the analysis.

Home range (HR) estimation techniques

Home Range estimators fall into two main groups: **location-based methods** ignore temporal information by assuming that points are independent from each other - an assumption rarely met by the short time intervals between GPS data points (Cagnacci *et al.*

2010; Recio *et al.* 2011; Pebsworth *et al.* 2012; Morris and Conner 2017); the second group are **movement-based methods**, that combine time and location data (in order to mitigate the impact of autocorrelation of the data), and can handle barriers or habitat edges. Rather than choose one method *a priori*, I conducted HR analyses using four different estimators, in order to provide a more complete and widely comparable picture of animal space use (Van Beest *et al.* 2011; Walter *et al.* 2011, 2015; Cumming and Cornélis 2012; Tétreault and Franke 2017; White and Garrott 2017). The four methods I selected consisted of two location based estimators, namely the **minimum convex polygon** (MCP, Mohr 1947) and **kernel density estimation** (KDE, Worton 1989). The two other methods I used were movement-based: **local convex hulls** with adaptive sphere-of-influence (LoCoH, Getz *et al.* 2007), and the **biased random bridge** algorithm (BRB, Benhamou 2011).

Home range estimates calculated using MCP are highly affected by the number of location points, yet it remains one of the most frequently used techniques to analyze animal movement, and thus it is often used to compare with earlier studies (Barg *et al.* 2005; Laver and Kelly 2008; Nilsen *et al.* 2008). The KDE method constructs HRs by defining a probability surface that reveals areas frequented by an animal (Horne and Garton 2006; Millspaugh *et al.* 2006). For a smoothing parameter, I used a plug-in bandwidth based on *a priori* knowledge of the distribution of the data (the mean distance since last location [DSLL] often is chosen, following recommendations by Walter *et al.* (2011). The movement-based LoCoH estimator involves an utilization distribution (UD, White and Garrott 2017) calculated by creating convex polygons (i.e. convex hulls) with an adaptive parameter *a*, that is based on the maximum distance existing between all pairs of locations within the dataset (Getz *et al.* 2007). The final estimator I used, BRB, is a movement-based kernel density estimator that uses time between data points to illustrate space use between locations independent of their density (Horne *et al.* 2007; Benhamou 2011). For this method, I used 4 hours as the upper recording time threshold (as that was the time-span between recorded relocations). Following the literature, I used the 95% contour to represent the annual HR (equivalent to where an animal occurs 95% of the time) and the 50% contour to define the “core area of use” (that represents the area where animal spend greater than 50% of their time during year) (Laver and Kelly 2008). Seasonal HRs only were estimated using LoCoH, as out of the four HR models considered in this study only LoCoH respects barriers to animal movement (e.g., rivers or lakes), which are important features of the landscape in the study area. Additional details on these different HR models can be found in in Walter *et al.* (2011), White and Garrott (2017), and references therein.

All analysis were done in R 3.6.2 software (R Core Team 2013) using the *adehabitatHR* package (Calenge 2011). The same package was used to generate maps of bighorn spatial range use overlaid on a basemap obtained through publicly available data from the European Union's Sentinel-2 satellite (European Space Agency 2020).

I considered seasonal migration to have occurred if the winter and summer ranges of individual bighorn bands had zero to 10% overlap (Brown 1992, Nicholson *et al.* 1997, Mysterud 1999). Following Poole *et al.* (2016), I termed rams that displayed distinct seasonal ranges as "migratory", and rams that did not show such patterns as "sedentary". Migration distance was defined as the horizontal distance between seasonal range centers of activity (centroids; Hayne 1949; Mysterud 1999), with the centroid calculated as the mean UTM coordinates of the locations for a ram band in each season (Wildsight Golden 2019). To look for potential vertical migration, the elevation of each location point was extracted from digital elevation model (DEM) of 25 m spatial resolution obtained from B.C. Data Catalogue (2019). Using these data, the daily mean elevation of each ram was computed by averaging the corresponding elevations for each of the six daily location points (see Table 2.4). These mean daily elevations then were aggregated at the seasonal to develop an elevation movement profile level for each ram band. Overlap was calculated as the proportion of each ram band seasonal HR that overlapped with each other seasonal HR (Winner *et al.* 2018).

RESULTS

Between April 2015 and December 2018, a total number of 142,201 location data points were obtained from 40 collared animals ($\bar{x}$ = 3,555, SD = ±2,031, range 110-7082). A total of 138,799 data points were used to calculate range size estimates for an average of 3,469 per ram (SD = ±2,102.31). Other than the software issue outlined above, the transmitters had few technical failures (missed location readings). The horizontal dilution of precision (HDOP) was low (less than 10) most of the time (99.97%). Five rams were excluded from seasonal HR due to an insufficient length of the data collection period for these animals (see Appendix 1).

Table 2.1 summarizes the model parameters and associated estimates of HR areas of the four bighorn bands studied. Maps of these HRs are presented in Appendix 2, and an example data set for a single ram is presented in Fig. 2.1. As expected, the estimates obtained from the four methods differed in size and degree of fragmentation. The single-polygons produced by the MCP method represented the largest range size estimates for the bands. This was particularly noticeable for the Spatsum band where a large portion of area with no recorded points was incorporated into the polygon (see Appendix 2, Fig. 3a). The range area estimates produced using the KDE method were not spatially contiguous but rather consisted of multiple polygons that more accurately depicted intensity of space use and produced home range estimates smaller than the MCP. The two kernel methods (KDE and BRB) produced similar estimates (in terms of shape, distribution, and size). The proportion of core area (50% isopleth) to total home range (95% isopleth) for the estimation techniques was consistent and represented 14% (±0.8) of annual home ranges, with the exception of MCP method where the proportion was 19% (±12).

Estimates of seasonal range areas were calculated for three of the four bands (Table 2.2). The Chasm band was not included in this analysis due to a limited amount of data. Maps of these seasonal ranges are presented in Appendix 3. Based on this analysis, all bands displayed considerable seasonal variation in their HR sizes. For the Battle Creek and Spatsum bands, HR estimates were at their minimum during winter, whereas for the Kamloops Lake band the winter HR was slightly larger than that for the spring/summer season. Overall, the Spatsum bighorns showed much more seasonal variation in HR size (Fig. 2.2). Analysis of seasonal ranges of each band showed high degree of overlap across the seasons (Table 2.3). The aggregated elevation values for the different seasons appeared similar for each band (see graphs in Appendix 4 and table 2.4), with the least change for Kamloops Lake sheep and the greatest change in Spatsum sheep.

Table 2. 1: Comparative annual home range estimates in km^2 for Bighorn Sheep ram bands monitored with GPS collars in the Thompson Region of British Columbia, Canada, 2015-2018. Four different estimators are show (MCP, KDE, LoCoH and BRB) with two variants based on the number of location points involved in the calculations (95% and 50%, respectively). Also shown is the smoothing parameter *h* (m) used in the KDE estimators and adaptive sphere-of-influence parameter *a* (m) used in the calculation of LoCoH. For the BRB method, the T_{max} was set to 4 hours. See Methods for details on each estimator.

	Battle Creek	Kamloops Lake	Spatsum	Chasm
h	320.5	337.5	425.3	258.2
a	31,298	46,093	63,549	34,599
MCP 95%	117.8	344.2	1,344.6	27.6
MCP 50%	35.9	21.5	277.9	10.6
KDE 95%	61.5	64.5	143.9	18.7
KDE 50%	9.9	9.4	19.2	1.8
LoCoH 95%	30.0	38.5	87.7	7.3
LoCoH 50%	4.6	4.8	12.7	1.1
BRB 95%	65.3	71.5	157.5	22.6
BRB 50%	9.9	9.7	20.3	1.4

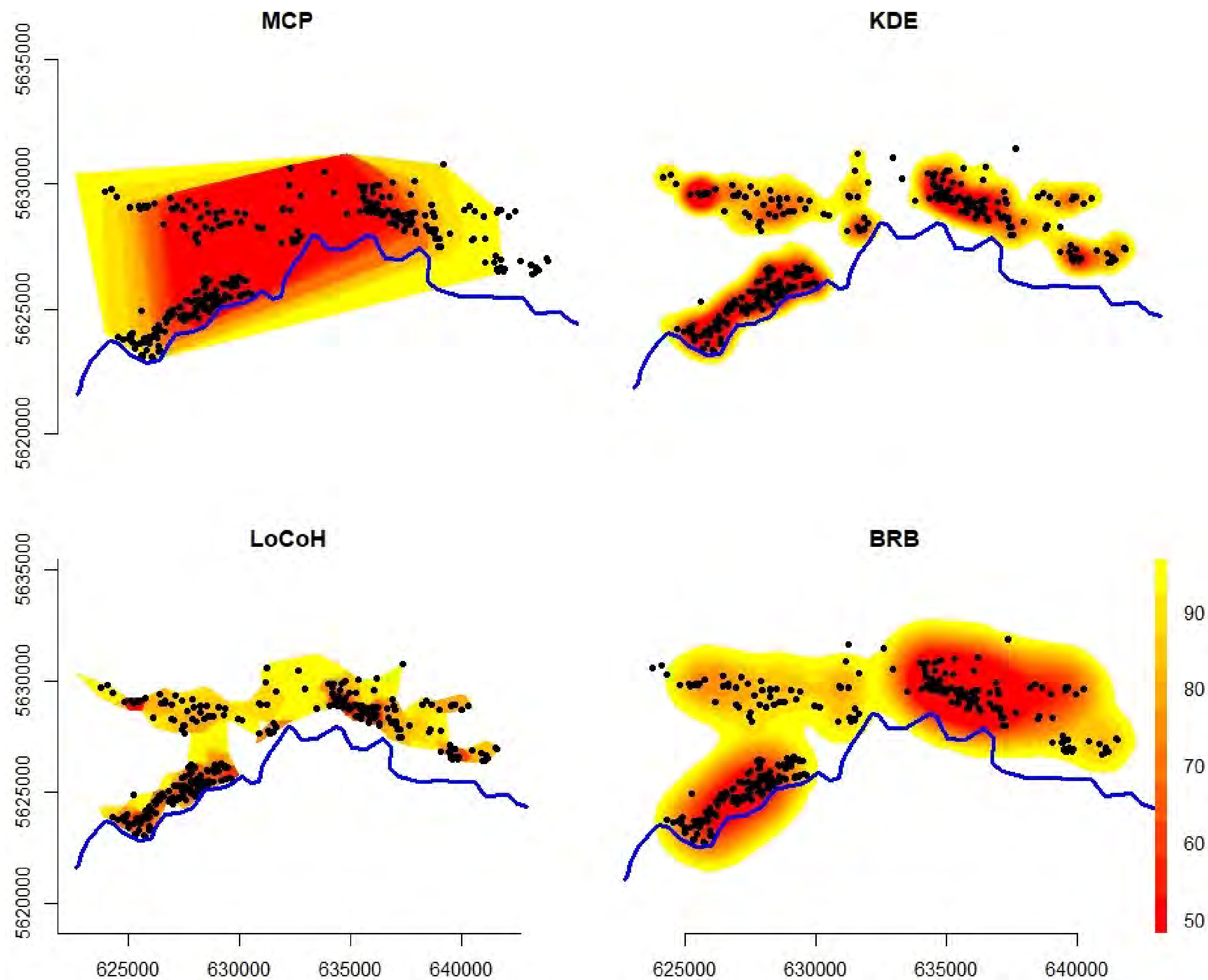

Fig. 2. 1: Example data set of a single ram (id: 01BC) from the Battle Creek herd showing differences in home range estimates produced by different home range methods; located on the right side is the gradient legend showing the volume isopleths (%); Thompson River is marked with blue line; maps in UTM coordinates.

Table 2. 2: Summary of seasonal home ranges (in km^2) for three Bighorn Sheep (*Ovis canadensis*) ram bands, using the LoCoH estimator (see Methods). Seasons were defined as: Winter Dec 1st-Mar 31st, Spring/Summer Apr 1st-Aug 24th, Autumn Aug 25th-Oct 24th, Rut Oct 25th-Nov 30th. See Methods text for rationale. Insufficient data were available for the Chasm band.

Ram band	Winter		Spring/Summer		Autumn		Rut	
	95%	50%	95%	50%	95%	50%	95%	50%
Battle Creek	14.62	2.17	23.78	3.95	34.75	7.24	29.79	7.36
Kamloops Lake	26.46	3.47	25.41	3.37	39.33	7.84	43.20	5.18
Spatsum	38.09	5.91	80.90	16.86	56.74	7.79	63.24	7.97

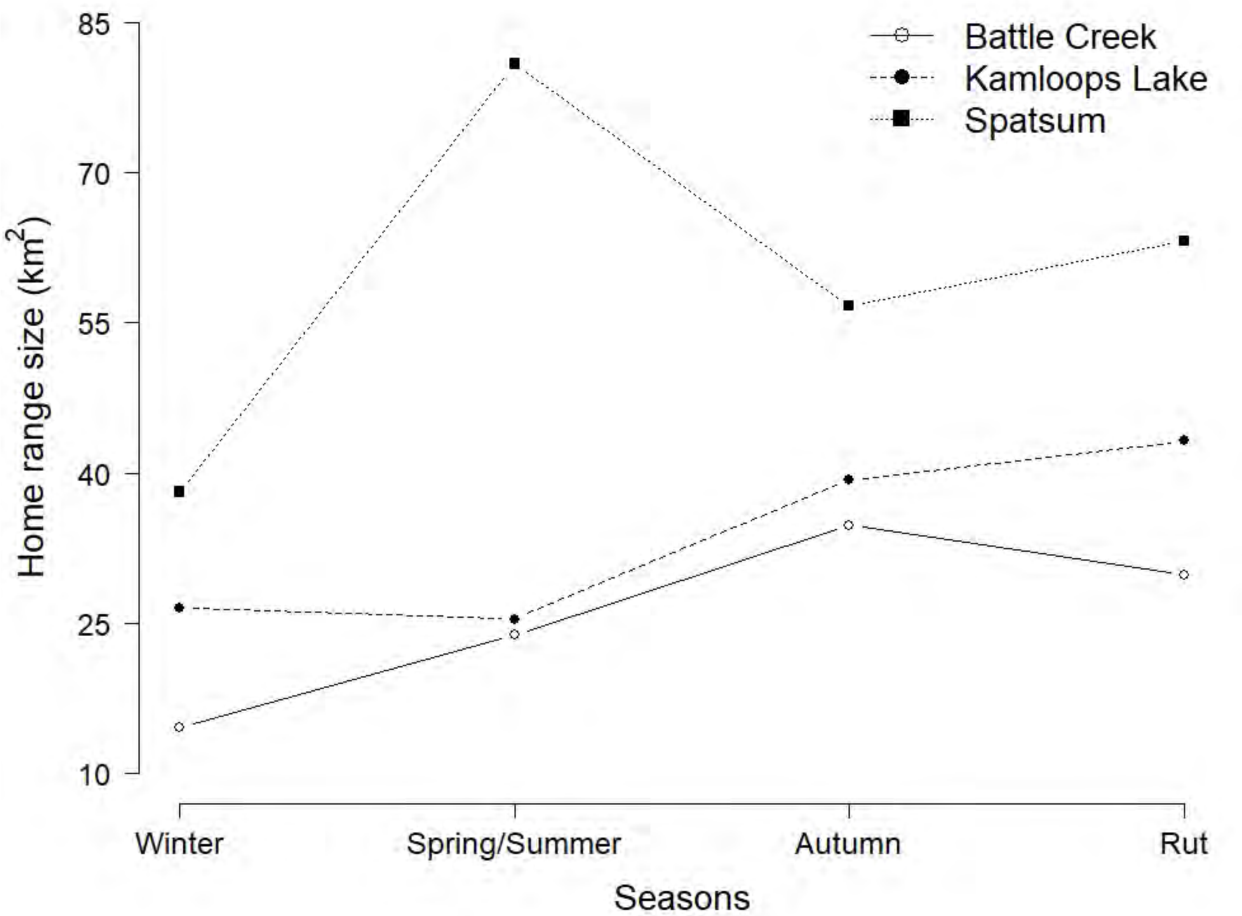

Fig. 2. 2: Seasonal variation in home range size (km^2, Local Convex Hull estimate) for three bands of Bighorn Sheep (*O. canadensis*) in the Thompson Region of British Columbia, Canada, collected in 2015-2018 (seasonal data was pooled together). See text for the range of dates associated with each season.

Table 2. 3: Shows percent of overlap between home ranges during different seasons calculated for three sets of Bighorn Sheep (*Ovis canadensis*) rams bands within the Thompson Region of British Columbia, Canada. See text for the working definition of the four seasons. Seasonal home ranges were obtained with LoCoH estimator.

	Spring/Summer	Autumn	Rut
BATTLE CREEK			
Winter	41.8%	32.7%	34.6%
Spring/Summer	-	44.8%	28.9%
Autumn	-	-	50.0%
KAMLOOPS LAKE			
Winter	56.8%	49.4%	42.0%
Spring/Summer	-	43.2%	35.5%
Autumn	-	-	59.7%
SPATSUM			
Winter	29.9%	44.6%	30.8%
Spring/Summer	-	48.6%	40.1%
Autumn	-	-	35.6%

Table 2. 4: Summary of statistics of elevation (in m) of recorded locations of seasonal home ranges for Battle Creek (13 rams), Kamloops Lake (11 rams), and Spatsum (14 rams) bands within the Thompson Region of British Columbia. See text for the working definition of the four seasons.

	Winter	Spring/Summer	Autumn	Rut
BATTLE CREEK				
Mean	510	611	682	604
Range	295-1,000	295-1,206	295-1,277	295-1,188
SD	±140	±200	±221	±197
N locations	11,671	23,722	7,593	5,891
KAMLOOPS LAKE				
Mean	478	510	552	539
Range	335-897	335-1,084	334-1,124	3341,329
SD	±123	±143	±176	±172
N locations	12,789	29,620	9,190	6,128
SPTATSUM				
Mean	515	654	682	490
Range	328-1,172	246-1,320	254-1,415	228-1,525
SD	±190	±223	±264	±242
N locations	9,765	15,774	4,800	4,008

The only interaction between the bands was observed for Battle Creek and Kamloops Lake bighorns during the rut seasons at the west end of Kamloops Lake (2.57% of their 95% KDE HRs overlapped). No other commingling between those rams was observed. Locations of only one ram (Spatsum herd, WLH ID: 15-6357) were found on the other side of Thompson River (approx. 15km south of Ashcroft, BC). This confirms connectivity between the Spatsum herd that resides on the east side of Thompson River and the neighboring Spence's Bridge herd on the west side of Thompson River (that herd is part of the Fraser River metapopulation). As only a small proportion of the animals were monitored (i.e. 14 rams from Spatsum herd that consist of approx. 200 sheep) it is possible the data underestimate the connectivity between those and neighbouring herds. Other than that there was no data locations showing any connectivity between bighorns separated by Thompson River and/or Kamloops Lake.

Discussion

This study contributes to a better understanding of the ecological determinants of home range behaviour and dynamics in bighorn populations. This study revealed atypical movements of bighorn bands both within and across seasons, while demonstrating the importance of carefully selecting the appropriate home range estimator. Although I did not identify a single method that is preferable for this type of study, my results clearly show shown that the method of home range estimation will have a significant effect on the results. Thus, expert opinion and the intended use of the estimated home range should inform the selection of the most appropriate estimation method.

The high degree of overlap between the seasonal home ranges of each band suggests non-migratory latitudinal movements and sedentariness. My findings agree with recent studies (Jesmer *et al.* 2018; Lowrey *et al.* 2019; Lula *et al.* 2020) that have shown that restored Bighorn Sheep populations, such as those in the Thompson Region, that were successfully re-introduced in the 1960's, exhibit less variable migrations. However, the majority of the native populations of "California" form Bighorn Sheep in the Interior of British Columbia do not show migratory movement patterns (Procter, pers. comm., FLNRORD). The information from this study also can be used to assess potential interactions with domestic animals (BC Wildlife Health, Habitat Conservation Trust Foundation) that concern the risk of disease transmission (see Chapter 3), as well informing management recommendations that will enable populations of Bighorn Sheep to persist into the future.

Despite a lack of barriers and the widespread availability of habitat, the sheep in the four study bands moved relatively little, suggesting persistence in this region does not require the extensive movement behaviour demonstrated by herds elsewhere. The autumnal rains and mild winter temperatures typical in this region results in the regrowth of grasses, creating a singular habitat that provides enough forage in later seasons, and thus eliminates the need for the bighorns to move to more distant regions. Poole *et al.* (2018) provided annual and winter range areas for eight subpopulations of bighorns in south-east British Columbia, with an estimated 715 individuals ranging from 36.5 km^2 to 175.9 km^2 (the estimation technique was not provided). In another study, Dibb (2006) estimated the HR of 10 rams at Radium Hot Springs, BC at 146.9 km^2 (MCP) and 32.7 km^2 (90% KDE).

Interestingly, in my study, the largest seasonal home range for each band occurred in the rut season, despite this being the shortest season (only 40 days) by definition. This likely reflects the foray behaviour of adult rams seeking mating opportunities. Seasonal HR of each band showed a high degree of overlap across the seasons. It suggests that those rams did not move to spatially-separated seasonal ranges. They appear to be relatively sedentary and do not display typical migratory behaviour between seasonal ranges. The study data support the suggestion that ungulates living in lowlands tend to exhibit non-migratory behaviour (Nahlik *et al.* 2009, Kamler *et al.* 2008), while in mountainous regions with strong seasonal spatial variation of critical resources, ungulates tend to migrate regularly (Luccarini *et al.* 2006, Zweifel-Schielly *et al.* 2009). This behaviour obviously will influence estimates of home range sizes.

Another explanation for why the study herds appear relatively sedentary and isolated from one another is that they are relatively “new” on the landscape. The bands in this study were associated with translocated herds in 1920s and 1960s and augmented in late 1990s (Demarchi *et al.* 2000), and thus may still be developing migratory patterns. Restrained seasonal migrations have been observed for translocated Bighorn Sheep, moose (*Alces alces*), and woodland caribou (*Rangifer tranadus caribou*) (Warren *et al.* 1996; Leech *et al.* 2017; Jesmer *et al.* 2018). Populations translocated into novel environments are less migratory than native populations that through continuous presence on the landscape have developed a “knowledge” of the area (Jesmer *et al.* 2018; Lowrey *et al.* 2019). Translocations into mountainous regions may prompt animals to develop elevational migrations that follow the “green wave” of newly emergent vegetation (Lowrey *et al.* 2019); these conditions are not present for bighorn populations along the Thompson River. Reduced migratory behaviour may contract home range size, in turn leading to small populations with limited range expansion.

Although I identified the LoCoH method as the most appropriate method for depicting the movements of my study herds, all studies involving one or more estimators are limited in their depiction of a “true” home range. A limitation of this study (and that of many mammals) is that no single home range estimator provides a “true” depiction of home range. Powell and Mitchell (2012) argued that mammals constantly are updating the cognitive map of their home range, and the estimates of their home range are only valid for a specific point in time. Kernel-based models therefore can be used to predict areas in which animals are likely to be at a point in time. Several simulation studies have begun to overcome this problem by using artificial tracking data with a known underlying distribution to test for the home range estimator best able to predict utilization distribution (e.g. Allen *et al.* 2016, Mancinelli *et al.* 2018). An estimate of a HR is, at best, a limited model of reality, being limited by the statistics used to approximate an animal’s behavior, and thus should not be taken as the final approximation of an animal presence on the landscape. The delineation of the HRs of those four bands in the study area does exclude presence of an animal in areas outside of those HRs.

The results of my study support the assertion of Bolger (2008) that management and conservation plans for ungulates need to account for the plasticity (or lack of it in this case) of migration behaviour. Larger, mobile mammals require large areas, making them especially susceptible to modifications of the natural landscape through climate change or human development. Migratory behaviour may allow them to adjust the distance and timing of their migrations to spatial and temporal changes in plant phenology (including those brought on by climate change); however, non-migratory animals may have muted responses to these challenges. Relatively sessile populations that rely on a single range area may be more likely to be impacted through various demographic mechanisms (Soule 1980; Lowe and Allendorf 2010; Borg *et al.* 2017). However, non-migratory behaviour also present some advantages, such as reducing the risk of disease transmission with other subpopulations (Chapter 3). Clearly, the mechanisms responsible for herd movements, including migration, still need to be investigated for those animals demonstrating such on smaller landscape scales.

LITERATURE CITED

Advanced Telemetry Systems. 2013. ATS G2110E Iridium User Manual.

Allen, A. M., and N. J. Singh. 2016. Linking movement ecology with wildlife management and conservation. Frontiers in Ecology and Evolution, 3(JAN): 1–13.

Allen, C., L. Parrott, and C. Kyle. 2016. An individual-based modelling approach to estimate landscape connectivity for Bighorn Sheep (*Ovis canadensis*). PeerJ, 4, 2001.

Barg, J. J., J. Jones, and R. J. Robertson. 2005. Describing breeding territories of migratory passerines: Suggestions for sampling, choice of estimator, and delineation of core areas. Journal of Animal Ecology, 74(1): 139–149.

BC Conservation Data Centre. 2021. https://www2.gov.bc.ca/gov/content/environment/plants-animals-ecosystems/conservation- data-centre/explore-cdc-data/glossary-for-species-ecosystems-at-risk. Accessed 29 May 2021.

BC Ministry of Water Land and Air Protection. (2004). Bighorn Sheep (*Ovis canadensis*) in accounts and measures for managing identified wildlife. Accounts V. 2004, 19.

Benhamou, S. 2011. Dynamic approach to space and habitat use based on biased random bridges. PLoS ONE, 6(1).

Besser, T. E., E. F. Cassirer, K. A. Potter, K. Lahmers, J. L. Oaks, and S. Shanthalingam, S. 2014. Epizootic pneumonia of Bighorn Sheep following experimental exposure to *Mycoplasma ovipneumoniae*. PLoS ONE, 9(10).

Besser, T. E., F. E. Cassirer, C. Yamada, K. A. Potter, C. Herdon, and W. J. Foreyt. 2012. Survival of Bighorn Sheep (*Ovis canadensis*) commingled with Domestic Sheep (*Ovis aries*) in the absence of *Mycoplasma ovipneumoniae*. Wildlife diseases, 48(1): 2006–2007.

Besser, T. E., F. E. Cassirer, M. A. Highland, P. Wolff, A. Justice-Allen, and K. Mansfield. 2013. Bighorn Sheep pneumonia: Sorting out the cause of a polymicrobial disease. Preventive Veterinary Medicine. 108: 85-93.

Bolger, D.T., W. D. Newmark, T. A. Morrison, and D. F. Doak, D.F. 2008. The need for integrative approaches to understand and conserve migratory ungulates. Ecology Letters, 11: 63–77.

Borg, N. J., M. S. Mitchell, P. M. Lukacs, C. M. Mack, L. P. Waits, and P. R. Krausman. 2017. Behavioral connectivity among Bighorn Sheep suggests potential for disease spread. Journal of Wildlife Management, 81(1): 38–45.

Bowyer, R. T., V. C. Bleich, K. M. Stewart, J. C. Whiting, and K. L. Monteith. 2014. Density dependence in ungulates: A review of causes, and concepts with some clarifications. California Fish and Game, 100(3): 550-572.

Cagnacci, F., L. Boitani, R. A. Powell, and M. S. Boyce, M. S. 2010. Animal ecology meets GPS-based radiotelemetry: a perfect storm of opportunities and challenges. Philosophical Transactions of the Royal Society B: Biological Sciences, 365(1550): 2157–2162.

Calenge, C. 2011. Home range estimation in R: the adehabitatHR package. R! Package, 1–60. http://cran.r-project.org/web/packages/adehabitatHR/vignettes/adehabitatHR.pdf.

Carpenter, T. E., V. L. Coggins, C. McCarthy, Ch. S. O'Brien, J. M. O'Brien, and T. J. Schommer. 2014. A spatial risk assessment of Bighorn Sheep extirpation by grazing domestic sheep on public lands. Preventive Veterinary Medicine, 114(1): 3–10.

Chapman, E. J., and C. J. Byron. 2018. The flexible application of carrying capacity in ecology. Global Ecology and Conservation, 13: 1–12.

Clapp, J. G., J. L. Beck, and K. G. Gerow. 2014. Post-release acclimation of translocated low-elevation, non-migratory Bighorn Sheep. Wildlife Society Bulletin, 38(3): 657–663.

Courtemanch, A. B. 2014. Seasonal habitat selection and impacts of backcountry recreation on a formerly migratory Bighorn Sheep population in Northwest Wyoming, USA. MS thesis, University of Wyoming, Laramie, Wyoming, USA.

Cumming, G. S., and D. Cornélis. 2012. Quantitative comparison and selection of home range metrics for telemetry data. Diversity and Distributions, 18(11): 1057–1065.

DeCesare, N. J., and D. H. Pletscher. 2006. Movements, connectivity, and resource selection of Rocky Mountain Bighorn Sheep. Journal of Mammalogy, 87(3): 531–538.

Demarchi, R. A., C. L. Hartwig, and D. A. Demarchi. 2000. Status of the California Bighorn Sheep in British Columbia. BC Ministry Environment, Lands and Parks, Wildlife Branch, Victoria, BC. Wildlife Bulletin No. B-98., (March): 53 pp. https://pdfs.semanticscholar.org/ae96/a864cdf65a5ed12cf9fd4bc8b023abbdf7d6.pdf.

Demarchi, R. A. 2002. Bighorn Sheep, *Ovis canadensis*. Pages 433-454 *in* K. Paige (technical editor), Standards for managing identified wildlife, Version 2. Draft for technical review. Ministry of Water, Land and Air Protection, Biodiversity Branch, Victoria, BC. 492pp.

Dibb, A. 2006. Seasonal habitat use and movement corridor selection of Rocky Mountain Bighorn Sheep, near Radium Hot Springs, British Columbia. Parks Canada Agency.

Dürr, S., and M. P. Ward. 2014. Roaming behaviour and home range estimation of domestic dogs in Aboriginal and Torres Strait Islander communities in northern Australia using four different methods. Preventive Veterinary Medicine, 117(2): 340–357.

Dussault, Ch., R. Courtois, JP. Ouellet, J. H. Pettorelli. 2001. Influence of satellite geometry and differential correction on GPS location accuracy. Wildlife Society Bulletin 29(1):171-179.

Edwards, V. L., J. Ramsey, C. Jourdonnais, R. Vinkey, M. Thompson, and N. Anderson. 2010. Situational agency response to four Bighorn Sheep die-offs in Western Montana. 17th Biennial symposium northern wild sheep and goat council, (April 2010): 29–50.

Festa-Bianchet, M. 1986. Site fidelity and seasonal range use by bighorn rams. Canadian Journal of Zoology, 64(10): 2126–2132.

Festa-Bianchet, M. 1987. Seasonal range selection in Bighorn Sheep: conflicts between forage quality, forage quantity, and predator avoidance. Oecologia, (1988): 580–586.

Fieberg, J., and L. Börger. 2012. Could you please phrase "home range" as a question? Journal of Mammalogy, 93(4): 890–902.

Geist, V. 1971. Mountain Sheep: A study in behavior and evolution. The Journal of Wildlife Management, 36(2): 673.

George, J. L., D. J. Martin, P. M. Lukacs, and M. W. Miller. 2008. Epidemic *pasteurellosis* in a Bighorn Sheep population coinciding with the appearance of a domestic sheep. Journal of Wildlife Diseases, 44(2): 388–403.

Getz, W. M., S. Fortmann-Roe, P. C. Cross, A. J. Lyons, and S. J. Ryan. 2007. LoCoH: Nonparametric kernel methods for constructing home ranges and utilization distributions. PLoS ONE, 2(2).

Horne, J. S., and E. O. Garton. 2006. Likelihood cross-validation versus least squares cross-validation for choosing the smoothing parameter in kernel home-range analysis. Journal of Wildlife Management, 70(3): 641–648.

Horne, J. S., E. O. Garton, S. M. Krone, and J. S. Lewis. 2007. Analyzing animal movements using Brownian bridges. Ecology, 88(9): 2354–63.

Hundertmark, K. J. 2007. Home range, dispersal and migration. Pages 303-335 *in* Ecology and Management of the North American moose. 2nd edition. University Press of Colorado, Boulder, USA.

Jesmer, B. R., J. A. Merkle, J. R. Goheen, E. O. Aikens, J. L. Beck, and A. B. Courtemanch. 2018. Is ungulate migration culturally transmitted? Evidence of social learning from translocated animals. Science, 361(6406): 1023–1025.

Johnson, H. E., M. Hebblewhite, T. R. Stephenson, D. W. German, B. M. Pierce, and V. C. Bleich. 2013. Evaluating apparent competition in limiting the recovery of an endangered ungulate. Oecologia, 171(1): 295–307.

Krausman, P. R. 2000. An Introduction to the Restoration of Bighorn Sheep. Restoration Ecology, 8(4S): 3-5.

Kropil, R., P. Smolko, and P. Garaj. 2015. Home range and migration patterns of male Red Deer (*Cervus elaphus*) in Western Carpathians. European Journal of Wildlife Research, 61(1): 63–72.

Kuzyk, G., P. Dielman, B. Jex, C. Procter, A. Reid, and H. Schwantje. 2012. Population and harvest trends of Mountain Sheep and Mountain Goats in British Columbia. Biennial Symposium of the Northern Wild Sheep and Goat Council, 18, 87–102.

Laver, P. N., and M. J. Kelly. 2008. A critical review of home range studies. Journal of Wildlife Management, 72(1): 290–298.

Lee Baker, T. 2015. Habitat selection and spatial responses of Bighorn Sheep to forest canopy in north-central Washington. MS thesis, Washington State University.

Leech, H., D. E. Jelinski, L. DeGroot, and G. Kuzyk. 2017. The temporal niche and seasonal differences in predation risk to translocated and resident woodland caribou (*Rangifer tarandus caribou*). Canadian Journal of Zoology, 95: 809–820.

Lowe, W. H., and F. W. Allendorf. 2010. What can genetics tell us about population connectivity? Molecular Ecology, 19(15): 3038–3051.

Lowrey, B., K. M. Proffitt, D. E. McWhirter, P. J. White, A. B. Courtemanch, and S. R. Dewey. 2019. Characterizing population and individual migration patterns among native and restored Bighorn Sheep (*Ovis canadensis*). Ecology and Evolution, 9(15): 8829–8839.

Lula, E. S., B. Lowrey, K. M. Proffitt, A. R. Litt, J. A. Cunningham, C. J. Butler, and R. A. Garrott. 2020. Is habitat constraining Bighorn Sheep restoration? A case study. Journal of Wildlife Management 84 (3): 588–600.

Lyons, A. J., W. C. Turner, and W. M. Getz. 2013. Home range plus: A space-time characterization of movement over real landscapes. Movement Ecology 1, 2 (2013)

Mancinelli, S., L. Boitani, and P. Ciucci. 2018. Determinants of home range size and space use patterns in a protected wolf (*Canis lupus*) population in the central Apennines, Italy. Canadian Journal of Zoology, 96(8): 828–838.

Millspaugh, J. J., R. M. Nielson, L. L. Mcdonald, J. M. Marzluff, R. A. Gitzen, and C. D. Rittenhouse. 2006. Analysis of resource selection using Utilization Distributions. Journal of Wildlife Management, 70(2): 384–395.

Mohr, C. O. 1947. Table of equivalent populations of North American small mammals, The American Midland Naturalist, 37(1): 223–249.

Morris, G., and L. M. Conner. 2017. Assessment of accuracy, fix success rate, and use of estimated horizontal position error (EHPE) to filter inaccurate data collected by a common commercially available GPS logger. PLoS ONE, 12(11): 1–12.

Mueller, T., and W. F. Fagan. 2008. Search and navigation in dynamic environments behaviors to population distributions. Oikos, 117 (December 2007): 11.

Nilsen, E. B., S. Pedersen, and J. D. C. Linnell. 2008. Can minimum convex polygon home ranges be used to draw biologically meaningful conclusions? Ecological Research, 23(3): 635–639.

Onderka, D. K., and W. D. Wishart. 1984. A major Bighorn Sheep die-off from pneumonia in southern Alberta. In Proceedings of the Fourth Biennial Symposium of the Northern Wild Sheep and Goat Council. p. 356-363. Cody, WY: Wild Sheep Foundation.

Pebsworth, P. A., H. R. Morgan, and M. A. Huffman. 2012. Evaluating home range techniques: Use of Global Positioning System collar data from Chacma Baboons. Primates, 53(4): 345-355.

Poole, K. G., R. Serrouya, I. E. Teske, and K. Podarsky. 2016. Bighorn Sheep winter habitat selection and seasonal movements in an area of active coal mining. Canadian Journal of Zoology, 1–17.

Poole, K. G., I. E. Teske, K. Podrasky, J. Berdusco, C. Conroy, and R. MacDonald. 2018. Elk Valley, Kootnenay-Boundary Region - Bighorn Sheep cumulative effects assessment report.

Powell, R. A., and M. S. Mitchell. 2012. What is a home range? Journal of Mammalogy, 93(4): 948–958.

R Core Team. 2013. The R Project for Statistical Computing. http://www.R-Project.Org/.

Recio, M. R., R. Mathieu, P. Denys, P. Sirguey, and P. J. Seddon. 2011. Lightweight GPS-tags, one giant leap for wildlife tracking? An assessment approach. PLoS ONE, 6(12).

Sells, S. N., M. S. Mitchell, J. J. Nowak, P. M. Lukacs, N. J. Anderson, and J. M. Ramsey. 2015. Modeling risk of pneumonia epizootics in Bighorn Sheep. Journal of Wildlife Management, 79(2): 195–210.

Singer, F. J., M. E. Moses, S. Bellew, and W. Sloan. 2000. Correlates to colonizations of new patches by translocated populations of Bighorn Sheep. Restoration Ecology, 8(4S): 66–74.

Singer, F. J., C. M. Papouchis, and K. K. Symonds. 2000. Translocations as a tool for restoring populations of Bighorn Sheep. Restoration Ecology, 8(4S): 6–13.

Smith, T. S., P. J. Hardin, and J. T. Flinders. 1999. Response of Bighorn Sheep to clear-cut logging and prescribed burning. Wildlife Society Bulletin, 27(3): 840–845.

Soule, M. E. 1980. Thresholds for Survival: Maintaining fitness and evolutionary potential. Conservation Biology: an Evolutionary-Ecological Perspective, 151–170.

Spitz, D. B., M. Hebblewhite, T. R. Stephenson, and D. W. German. 2018. How plastic is migratory behavior? Quantifying elevational movement in a partially migratory alpine ungulate, the Sierra Nevada Bighorn Sheep (*Ovis canadensis sierrae*). Canadian Journal of Zoology, 96(12): 10.

Tétreault, M., and A. Franke. 2017. Home range estimation: examples of estimator effects. Pages 207-242 *in* Applied Raptor Ecology: Essentials from Gyrfalcon Research.

Van Beest, F. M., I. M. Rivrud, L. E. Loe, J. M. Milner, and A. Mysterud. 2011. What determines variation in home range size across spatiotemporal scales in a large browsing herbivore? Journal of Animal Ecology, 80(4): 771–785.

Walter, D. W., and J. W. Fischer. 2016. Manual of applied spatial ecology. Walter Applied Spatial Ecology Lab, Pennsylvania State University, University Park. (February): 1–178.

Walter, D. W., J. W. Fischer, S. Baruch-Mordo, and K. C. VerCauteren. 2011. What is the proper method to delineate home range of an animal using today's advanced GPS telemetry systems: The initial step. Pages 249-268 *in* Modern Telemetry.

Walter, D. W., D. P. Onorato, and J. W. Fischer. 2015. Is there a single best estimator? Selection of home range estimators using area-under-the-curve. Movement Ecology, 3(1): 10.

Warren, C. D., J. M. Peek, G. L. Servheen, and P. Zager. 1996. Habitat use and movements of two ecotypes of translocated Caribou in Idaho and British Columbia. Conservation Biology, 10: 547–553.

White, G. C., and R. A. Garrott. 2017. Home Range Estimation. Analysis of Wildlife Radio-Tracking Data, (April): 145–182.

Wildsight Golden. 2019. Golden Rocky Mountain Bighorn Sheep Project – Phase 1. https://wildsight.ca/branches/golden/golden-rocky-mountain-bighorn-project/

Winner, K., M. J. Noonan, C. H. Fleming, K. A. Olson, T. Mueller, D. Sheldon, and J. M. Calabrese. 2018. Statistical inference for home range overlap. Methods in Ecology and Evolution, 9(7): 1679–1691.

Worton, B. J. 1989. Kernel methods for estimating the utilization distribution in home-range studies. Ecology, 70(1): 164–168.

Zheng, R., L. M. Smith, D. J. Prosser, J. Y. Takekawa, S. H. Newman, and J. D. Sullivan. 2018. Investigating home range, movement pattern, and habitat selection of bar-headed geese during breeding season at Qinghai Lake, China. Animals, 8(10): 182.

Personal Communications:

Ayotte, Jeremy, RPBio, 2021, Phyla Biological Consulting, Salmon Arm, British Columbia

Hales, Gerad, RPBio, 2021, Wildlife Management Specialist, British Columbia Ministry of Forests Lands, Natural Resource Operations and Rural Development (BC FLNRORD), Kamloops, British Columbia.

Iredale, Francis J., RPBio, 2021, Wildlife Biologist, British Columbia Ministry of Forests Lands, Natural Resource Operations and Rural Development (BC FLNRORD), Kamloops, British Columbia.

Procter, Chris, RPBio, 2021, Wildlife Biologist, British Columbia Ministry of Forests Lands, Natural Resource Operations and Rural Development (BC FLNRORD), Kamloops, BC.

CHAPTER THREE: FORAY MOVEMENTS OF BIGHORN SHEEP AND IMPLICATIONS FOR RISK OF CONTACT WITH DOMESTIC SHEEP IN SOUTH-CENTRAL BRITISH COLUMBIA, CANADA

INTRODUCTION

Movement patterns represent key facets of any species' ecology, on any scale. For that reason, knowledge of these patterns is an important consideration when developing management plans. Recent technological and analytical advances in animal tracking have significantly improved the knowledge of where, when, and why species move (Tomkiewicz *et al.* 2010). Conceptual frameworks, such as the one presented by Allen and Singh (2016), illustrate how individual animal movement can be used to identify management actions and enhance conservation planning. Sometimes however, the movements of individuals are not predictable (in space and time), particularly in those species that exhibit a huge plasticity in movement and behaviour of individuals (Fryxell *et al.* 2005; Bolger *et al.* 2008). The movements of herding populations generally are interpreted collectively, particularly when multiple animals make consistent, concerted movements. However, such group movements often carry both benefits and consequences for the individuals and the groups (see Chapter 2).

Even within herding populations, individuals may conduct movements that are asynchronous with others in the herd. Such movements either may result in individuals permanently leaving the home range of the group (a form of dispersal - Bowler and Benton 2005), or making a temporary, exploratory movement whereby the individual eventually rejoins the herd. In some species, these exploratory movements serve as a prelude to actual dispersal (Killeen *et al.* 2014). Exploratory movements also play a role in providing connectivity between populations, while critically influencing individual fitness, demography and gene flow (Bohonak 1999; Bowler and Benton 2005; Cagnacci *et al.* 2010). For larger mammals, long-term telemetry data may be the best approach for documenting and testing predictions about exploratory movements out of herds, and/or determining evolutionary tactics such as sex-biased dispersal (Dobson 2013). For example, Killeen *et al.* (2014) identified male elk (*Cervus elaphus*) that undertook exploratory movements prior to dispersal. Reintroduced Scimitar-Horned Oryx (*Oryx dammah*) engaged in periods of wide-ranging exploratory movements before establishing home ranges, while decreasing the time available for foraging, vigilance and reproduction (Mertes *et al.* 2019). Exploratory movements of this nature are fairly common within many ungulates (Bowler and Benton 2005; Killeen *et al.* 2014).

The Bighorn Sheep (*Ovis canadensis*) is a North American ungulate (F. Bovidae) found throughout western North America. Although considered a herding species (Geist, 1971; Singer *et al.* 2000), exploratory movements by individuals outside of their herd's home range have been well documented in the scientific literature. Singer *et al.* (2001) applied the term 'foray' to these movements, and defined them as any short-term movement of an animal away from and back to its herd's home range. Forays of males, especially during the rut season, are thought to connect populations of Bighorn Sheep (Geist, 1971; Bleich *et al.* 1997; Boyce *et al.* 1997; Rubin *et al.* 1998), but the timing and extent of these movements vary by individual and age. For example, Festa-Bianchet (1986) reported rams in Alberta, Canada that were 48 km outside their core home ranges; in Montana, Bighorn Sheep were observed conducting several long-distance summer forays of up to 33 km (DeCesare and Pletscher, 2006). O'Brien *et al.* (2014) reported bighorns travelling 50 km from their core home ranges in Idaho, and Schroeder *et al.* (2010) reported that the mean daily forays of males were greater than those of females. Aside from the aforementioned benefits of forays, these movements also may serve as a vector for disease transfer, a very important issue in the management of Bighorn Sheep populations (Singer *et al.* 2000; Gross *et al.* 2000).

Extensive scientific literature in the last 35 years strongly indicates a link between disease in Bighorn Sheep and contact with domestic sheep (see Cassirer *et al.* 2017, and references therein). Direct contact between domestic and wild sheep during pen experiments resulted in a high probability of disease transmission and a high lethal outcome (Onderka *et al.* 1988; Foreyt, 1994; Foreyt and Silflow, 1996; Lawrence *et al.* 2010; Besser *et al.* 2012). In addition, numerous field observations have documented pneumonia outbreaks in Bighorn Sheep following contact with domestic sheep, reaffirming the high risk to the wild animals (Foreyt and Jessup, 1982; Goodson 1982; Coggins 1988; George *et al.* 2008). Pneumonia pathogens (*Mycoplasma ovipneumoniae* and genus *Pasteurella*) are the most common disease-causing organisms associated with die-offs of free ranging Bighorn Sheep (Besser *et al.* 2012). Those pathogens commonly are carried by domestic sheep that do not suffer deleterious effects (Miller, 2001; Dassanayake *et al.* 2009; Lawrence *et al.* 2010). Previous work has demonstrated that only 5% of bighorn herds of comparable size were able to persist after a disease outbreak (Singer *et al.* 2001). Given these disease epizootics significant impact on the health of Bighorn Sheep populations, there is a need to examine the specific factors that may facilitate disease transfer, including foray behaviour by individuals.

Although the majority of Bighorn Sheep occur in the western United States, numerous herds occur in British Columbia (BC), Canada, where they are assigned a provincial status of "blue-listed" (species of Special Concern, formerly Vulnerable - B.C. Conservation Data Centre 2021). At the same time, domestic sheep farming is a growing industry in BC due to increasing demand for lamb meat and wool prices, bringing an increased risk of disease transmission. Indeed, a recent agriculture census showed an increase in the number of sheep and goat farms in the Thompson-Nicola region of Southern Interior BC from 136 to 145 over five years (2011-2016, Statistics Canada 2020). In 2015, the BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD) initiated a telemetry study to examine the viability of bighorns in this region, given the potential for disease transmission to occur between the wild and domestic sheep herds, or between herds of bighorns. The study focused on males, as male bighorn have greater tendency to explore new areas (Singer *et al.* 2000) and thus to better understand the potential of their long-distance movements and to delineate exterior population boundaries.

In Chapter 2, I examined the movements of herds containing collared bighorn rams and their spatial relationship to one another. In this chapter I build upon concepts outlined by Clifford *et al.* (2009) to (1) create a model of Bighorn Sheep habitat suitability for the study area (source habitats assessment) and (2) model the risks of contact between Bighorn Sheep and domestic sheep given detected foray movements. Outputs from these models were used to describe the foray patterns in male sheep within this region, and at the same time, make predictions for the risk of disease contraction and the long-term viability of bighorn populations in this region.

METHODS

Study area

Satellite telemetry provided GPS positioning data (2015 to 2018) from 40 Bighorn Sheep rams distributed across 4 herds (Battle Creek, Kamloops Lake, Spatsum, and Chasm) in the Thompson Region within Central Interior of British Columbia, Canada at elevations of roughly 300 - 1,500 m. One of these bands (Chasm) could not be included in this analysis due to a limited amount of data (less than 1% of collected data points). The remaining three bighorn bands were in close proximity to one other, although two of them (Battle Creek and Kamloops Lake) were separated from the third one (Spatsum) by Kamloops Lake (approx. 2.5 km wide) and the Thompson River outflow (approx. 100 m wide) (see Fig. 1.3 in Chapter 1). Other bighorn herds exist on both sides (west and east) from the study area. Telemetry data were acquired using G2110E Iridium GPS collars (Advanced Telemetry Systems 2013) fitted to a sample of rams in each herd (for more details see Chapter 2). The GPS collars were programmed to collect 6 locations per day at 4-hour intervals.

Home range estimates

In this chapter I used the home range estimates that I calculated in Chapter 2 to assess the foray movements following convention of Calenge and Fortmann-Roe (2017). This home range has been termed the ‘core herd home range’ (CHHR) in the literature, but here, to keep it consistent across chapters, I refer to it simply as ‘home range’ (HR). The HRs were calculated using the kernel density estimate (KDE, Worton 1989), generated with the *adehabitatHR* package (Calenge and Fortmann-Roe 2017) in R - ver. 4.0.2 (R Core Team 2013). However, I also used the same program and package to provide HR estimates using the Local Convex Hull (LoCoH, Getz *et al.* 2007) method (Chapter 2).

Foray characteristics

I defined a foray as movement of an animal away from and back to its band home range (HR). I then calculated a maximum foray distance based on the furthest location point the ram was observed from the edge of the HR, and then determined whether the ram crossed each of a progressive series of 1-km-wide buffers surrounding the HR. Because the farthest observed foray in this study was 6 km from the edge of a HR, I calculated the crossing probabilities for buffers out to 6 km by totaling the number of forays for all collared animals and dividing by the total number of years of each individual's radiocollar data (Singer *et al.* 2001; O'Brien *et al.* 2014). That formula provides the rate of foray which specifies the number of forays one ram could travel in a year. Thus, this analysis examined how frequently and in what season foray movements occurred, provided the probability and rate of a bighorn ram leaving its HR, and identified how far beyond the HR the rams were likely to travel.

Habitat preferences and source habitat

I used a 'source habitat' model initially developed by the Hells Canyon Bighorn Sheep Restoration Committee (HCBSRC 1997) to identify areas of habitat considered suitable for use by Bighorn Sheep. This was based on work by Smith and Winn (1991), Gudorf *et al.* (1996), Schirokauer (1996), and Sappington *et al.* (2007), who all verified a strong preference by Bighorn Sheep for areas close to steep, rugged terrain into which they can flee for safety with neighboring open areas that provide sufficient forage. Using ArcGIS (ver. 10.7) I integrated six habitat components into this model to determine areas of source habitat for viable populations of Bighorn Sheep: (1) proximity to escape terrain defined by slopes of 27^{o} (slopes were averaged across 30 m^2 pixels and identified from standard U.S. Geological Survey digital elevation models), (2) areas within 300 m buffer around escape terrain, or 525 m if the terrain was bordered by escape terrain on two sides, (3) areas with at least 55% horizontal visibility (Johnson and Swift 2000); high visibility allows sheep to detect predators and maintain contact with other herd members, (4) grassland, rock, and open shrub as frequently used by Bighorn Sheep (Schirokauer 1996); all vegetation types were based on a Normalized Difference

Vegetation Index (NDVI) layer calculated from the B4 (red) and B8 (NIR) bands of the multispectral imager carried aboard the European Union's Sentinel-2 satellites (European Space Agency, 2020), (5) natural barriers that generally are impassable for Bighorn Sheep, such as large lakes, and (6) developed areas (e.g., commercial or industrial developments, and structures) where noise disturbance results in avoidance by bighorns. These criteria are described in greater detail by Zeigenfuss *et al.* (2000). All areas within the study area were assigned to one of three habitat classes: source habitat, connectivity area, and non-habitat. A description of source habitat is provided above; connectivity areas were defined as the 350 m buffer around source habitat, or 525 m if between two source habitat areas (a meadow area between two canyons), and all remaining areas were classified as non-habitat (Zeigenfuss *et al.* 2000).

Private lands and domestic sheep allotments

Data were unavailable for the spatial or temporal distribution of current domestic sheep and goat operations in the region. I therefore used the location of active titled parcels of land (private land) as a crude guide to the potential presence of domestic sheep. The area of all private lands located within or adjacent to Bighorn Sheep habitat was derived from spatial files provided by Ministry of Citizen Services (2020). Further, 80% of private lands in the study area have Agricultural Land Reserve status (ALC 2020), and thus carry no restrictions on raising domestic sheep or goats. Spatial overlap between private lands and Bighorn Sheep presence was assessed by overlaying HR areas and private lands boundaries and calculating the percentage of that overlap.

Risk of Contact Tool (RoCT)

Following a remand by the Chief of the American Forest Service (USDA Forest Service 2005), the Payette National Forest developed a Risk of Contact Tool (RoCT) for calculating the probability and rates of contact between Bighorn Sheep and active domestic sheep allotments (O'Brien *et al.* 2014). The model uses six data components: (1) a herd home range, (2) a source habitat model, (3) foray distance probabilities, (4) relative habitat preference based on proportion of location points on each class of source habitat model, (5) the herd size and sex ratio: for Battle Creek herd: 120 animals with 30 rams, Kamloops Lake herd: 210 animals with 65 rams, Spatsum herd: 195 animals with 30 rams (Procter and Iredale, Pers. comm., FLNRORD), and (6) private parcels as approximation of active domestic sheep allotments.

The result is a geospatial analysis application that can be used by field wildlife biologists and resource managers. It calculates and maps areas where collared animals spend most of their time (the HR). From this can be derived the frequency and seasonality of foray movements, the distance away from HR an animal is likely to travel in relation to provided source habitat, and the probability of a ram or ewe to reach a domestic sheep location (FS/BLM Bighorn Sheep Working Group 2020). The model provides a framework for addressing the possibility of contact and/or disease transmission and it has been widely adopted by Field Offices in US wildlife management agencies (Payette National Forest 2010; US Rio Grande National Forest 2013; Mack *et al.* 2017; US Department of the Interior Bureau of Land Management 2019). I used the RoCT to provide additional insights into my analysis on risk of disease transmission.

Results

Home range estimates

Home range (HR) areas estimated with the KDE method were on average twice the size of those estimated by the LoCoH method (see Table 2.1, Chapter 2). Further, when comparing the HR estimate and the six associated buffer zones, the KDE estimates always were greater in size, and the rate at which the estimates increased was consistent (see Fig. 3.1). Thus the two home range estimation methods provided similar results for the foray analysis; given the potential impacts of disease transmission to the bighorn herds, I used the larger HRs (as it provides more robust buffer zone) as the base for assessing the risk of contact between wild bighorn herds and domestic sheep. The HRs of three Thompson Region Bighorn Sheep ram bands included ~98% (134,646/137,591) of all location data points. The HRs, especially for the Spatsum band,

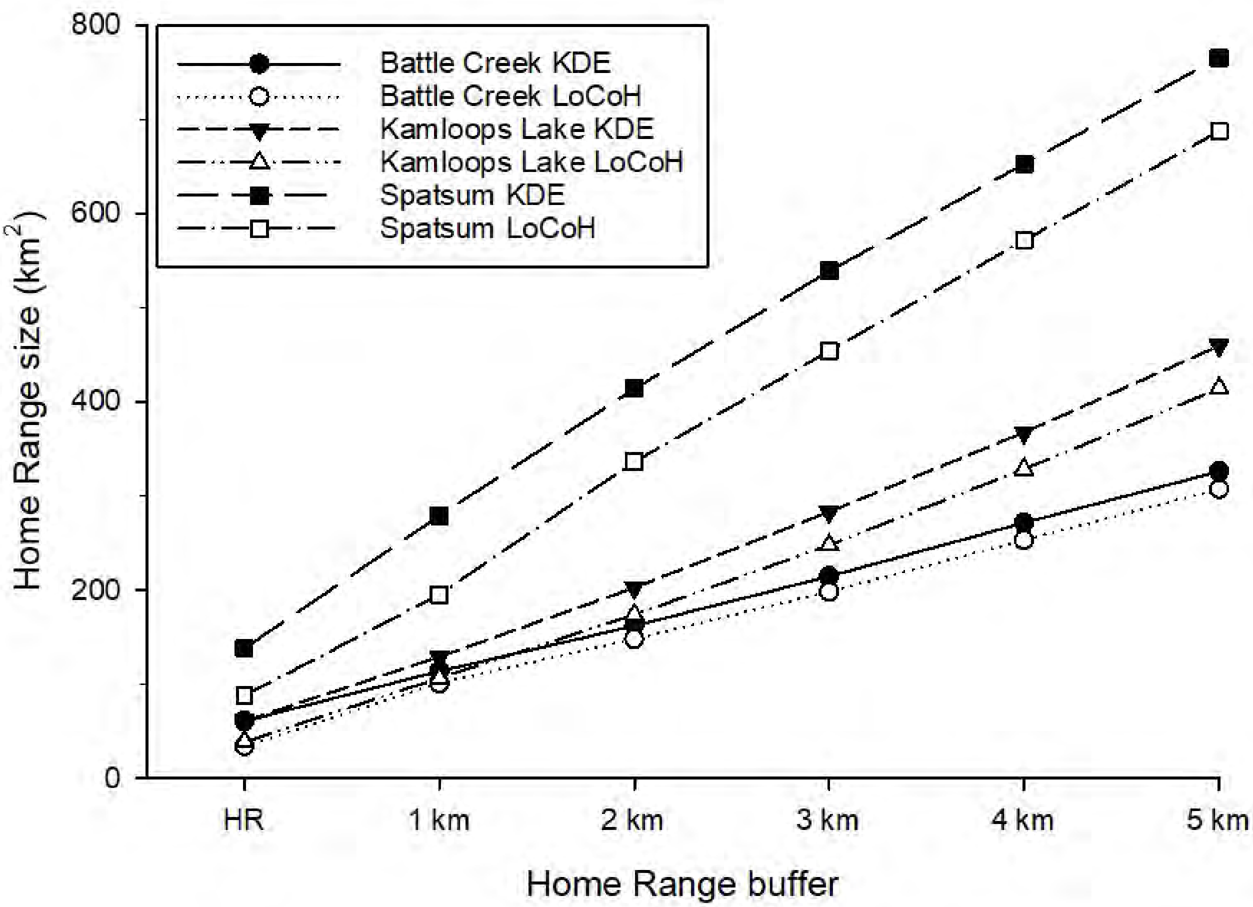

Fig. 3.1: Comparison of two home range estimation methods: KDE (Kernel Density Estimation) and LoCoH (Local Convex Hull) for three Bighorn Sheep ram bands in Thompson Region within Central Interior of British Columbia. For each band, the increase in home range size across the initial and subsequent estimates (using buffer-zones with 1 to 5 km radii) were consistent between the two estimators, with the KDE estimate being consistent greater than the corresponding LoCoH estimate.

were not spatially contiguous but rather consisted of multiple polygons that played a role in defining location points as foray movements (Fig. 3.2, Table 3.1).

Foray characteristics

In total only 2.1% (2,945/137,591) of ram location data points occurred outside the respective animals' HR. By examining these points, I found 105 unique foray movements demonstrated by approximately 82% (31/38) of the rams; when converted to animal-years (years of animal's radiocollar data), I found 48% (31 rams/65.1 animals' years of observation) of the rams forayed beyond their HRs. Most forays were short-distance movements (62% < 1 km) or between HR polygons; only 10.5% of them reached at least 4 km. Only one foray (1/105) extended more than 5 km from the respective HR, conducted by a ram (ID: 35KL) from the Kamloops Lake band that travelled 5.3 km from its band HR (Table 3.1, Fig. 3.2).

Out of the 105 identified foray movements (outside of the respective HRs), 38% (40/105) occurred during the spring-summer months and 62% (65/105) during the autumn-winter months (Table 3.2). Figure 3.3 shows the relationship between the number of forays and their season of occurrence, for the three bands together and separately. More than a half of these forays (65%, 68 out of 105) fell within the first 1 km buffer zone surrounding the ram's band home range (Fig. 3.4) Six of these foray movements brought the animals into the home range polygon calculated for a neighboring herd (traveled by three rams from Battle Creek band to Kamloops Lake band) and these movements occurred during the rut season. Also one ram from the Spatsum band forayed to the neighbouring Spence's Bridge herd (that herd is part of the Fraser River metapopulation and was not included in this study). None of the rams in this study were found to change band membership during the data collection period.

The rams in this study did not travel more than 6 km from the HRs during their forays. This result is unusual, given that the literature reports much longer foray distances (Festa- Bianchet 1986; DeCesare and Pletscher 2006; O'Brien *et al.* 2014), prompting me to examine

Table 3. 1: Distribution and frequency of foray movements outside of home ranges of three Bighorn Sheep ram bands in Thompson Region, British Columbia, 2015–2018. Foray distances were stratified into 1-km buffers emanating out from home range. Rate of foray was determined by totaling the number of forays for each 1km-wide buffer and dividing by the total number of years of individual's radiocollar data (animal years of observation).

	Battle Creek (N=13)		**Kamloops Lake (N=11)**		**Spatsum (N=14)**		**All 3 bands (N=38)**	
Buffer width	**No. of forays**	**Rate of forays**	**No. of forays**	**Rate of forays**	**No. of forays**	**Rate of forays**	**No. of forays**	**Rate of forays**
1 km	15	0.67	48	1.86	5	0.30	68	1.04
2 km	8	0.36	8	0.31	5	0.30	21	0.32
3 km	2	0.09	4	0.16	2	0.12	8	0.12
4 km	3	0.13	1	0.04	2	0.12	6	0.09
5 km	-	-	-	-	4	0.24	4	0.06
6 km	-	-	1	0.04	-	-	1	0.02

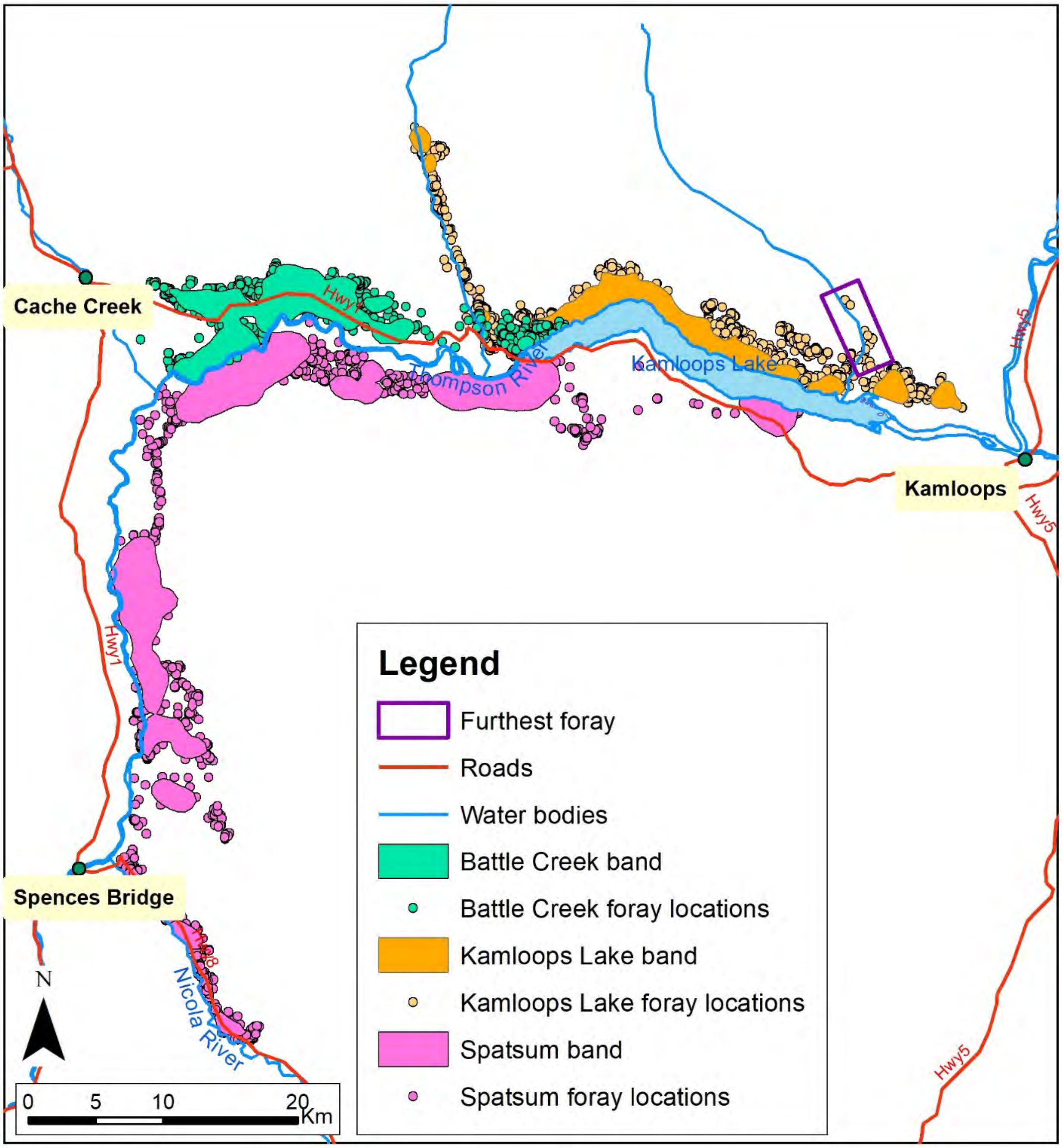

Fig. 3. 2: Location map of home ranges (HR) and their disjoint polygons of three Thompson Region Bighorn Sheep ram bands within the Central Interior of British Columbia, Canada. Two of those bands (Battle Creek and Kamloops Lake) are separated from the third (Spatsum) by Thompson River and Kamloops Lake. Only extrapolated foray locations and their close proximity to band's HR are displayed, the furthest foray movement is marked with purple polygon.

Table 3. 2: Summary of foray movements in spring-summer and autumn-winter seasons outside of home ranges (HR) of three Bighorn Sheep bands in Thompson Region within the Central Interior of British Columbia. Foray rate was determined by totaling the number of forays for each season and dividing by the total number of years of individual's radiocollar data (animal years of observation).

Band	Spring-Summer forays	Autumn-Winter forays	Total foray number	Max distance (km)	Animal-years of observation	Spring-Summer rate	Autumn-Winter rate	Total rate
Battle Creek (N=13)	1	24	25	4.9	22.4	0.04	1.07	1.12
Kamloops Lake (N=11)	30	32	62	5.3	25.8	1.16	1.24	2.40
Spatsum (N=14)	9	9	18	4.5	16.9	0.53	0.53	1.07
All 3 bands	**40**	**65**	**105**	**5.3**	**65.1**	**0.61**	**1.00**	**1.61**

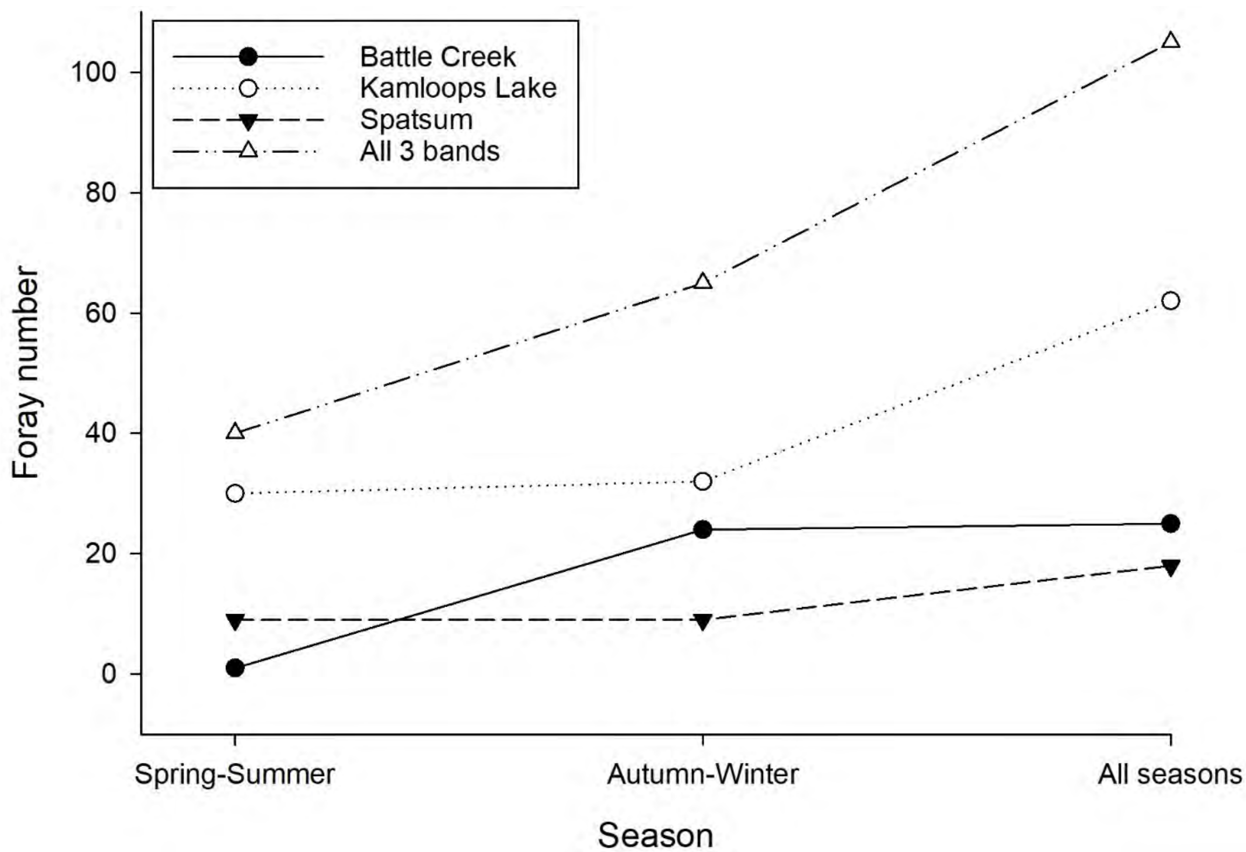

Fig. 3. 3: The relationship between the season of occurrence and the numbers of forays of individuals from three Bighorn Sheep ram bands in Thompson Region within the Central Interior of British Columbia (2015-2018).

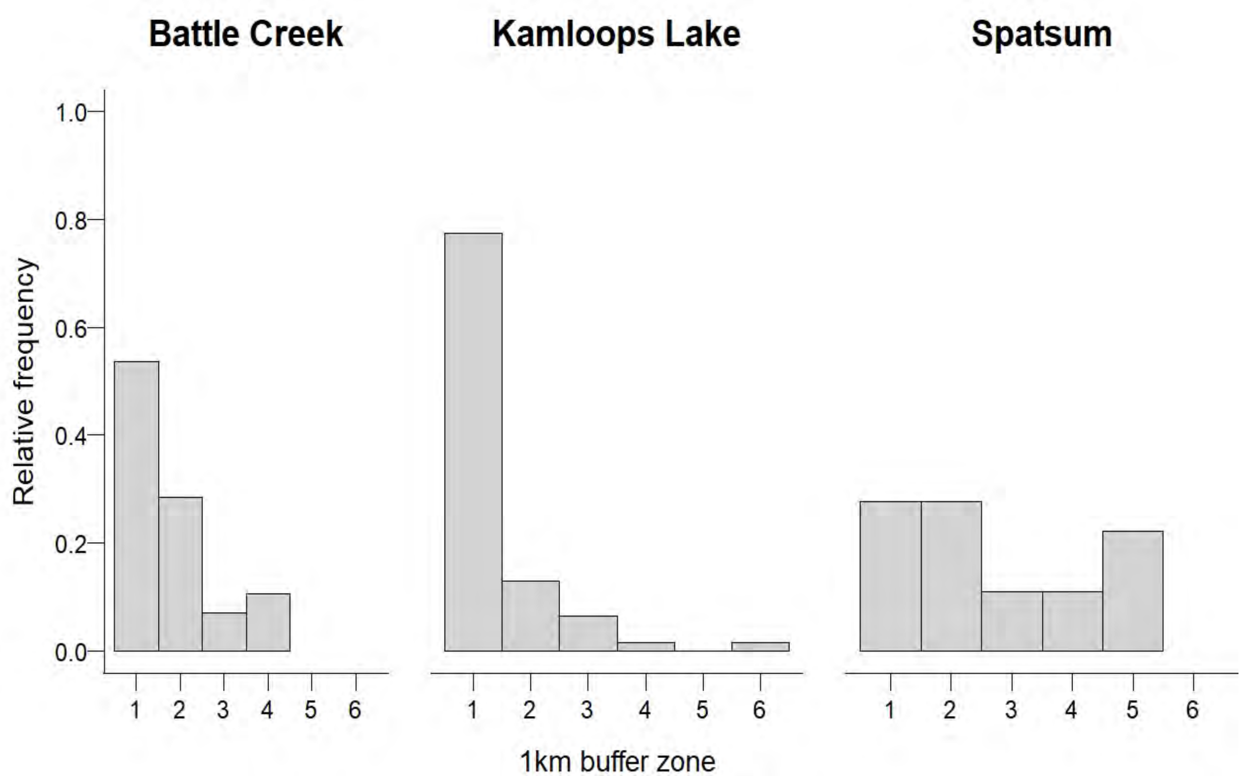

Fig. 3. 4: Distribution of distances (km) traveled on foray movements of three Bighorn Sheep ram bands. The traveled distance is measured from the nearest boundary of the **band's home range (HR)**. The y-axis represents proportion of foraying rams that reach each 1-km-wide buffer zone along the x-axis. HR and foray movement distances are based on telemetry data collected from 38 rams from Thompson Region within the Central Interior of British Columbia (2015-2018).

foray movements in relation to each ram's individual location history (thus, treating foray as a movements outside of *individua*l ram's home range, instead of band's home range). With this approach, 29 rams (76%) demonstrated exploratory movements outside of their own home range, but seven of them (4%) traveled more than 10 km away, with the longest distance travelled being 35.2 km (ram 24S from Spatsum band, Fig. 3.5). More than a half of these forays (57%) still fell within the first 1 km buffer zone surrounding the ram's home range (Fig. 3.6). Out of 167 identified forays outside the individual ram's home ranges, 42% (70/167) occurred during spring-summer seasons, and 58% (97/167) during autumn-winter seasons.

Habitat preferences and source habitat

The source habitat model classified 42% of the study area as potential source habitat for those herds. Only 9.2% of the source habitat is currently occupied by the collared bighorns (based on their home range estimates). The habitat preferences for each class were as follow: for class 'habitat': 1.00 (as a standard preference of bighorns), for class 'connectivity areas': 0.02 (1.9% of location points were within that class), and for class 'non-habitat': 0.0009 (only 0.09% of location points were outside habitat and connectivity area classes). While validating the source habitat model accuracy for the study area, 97% of the rams' locations were found within mapped source habitat. The source habitat model identified 2,831 km^2 of suitable Bighorn Sheep habitat within study area (Table 3.3, Fig. 3.7, study area size: 6,754 km^2). For all of the three bighorn bands, the accuracy of predicted habitat use was greater or close to recommended 75% (Zeigenfuss *et al.* 2000). There was 77%, 84% and 73% overlap of HRs with source habitat for the Battle Creek, Kamloops Lake and Spatsum bands, respectively.

Private lands and domestic sheep

The private lands spatial data, used as an crude approximation of possible domestic sheep presence, revealed 2,753 km^2 of private land lay within the study area (size: 6,754 km^2) with a nearly

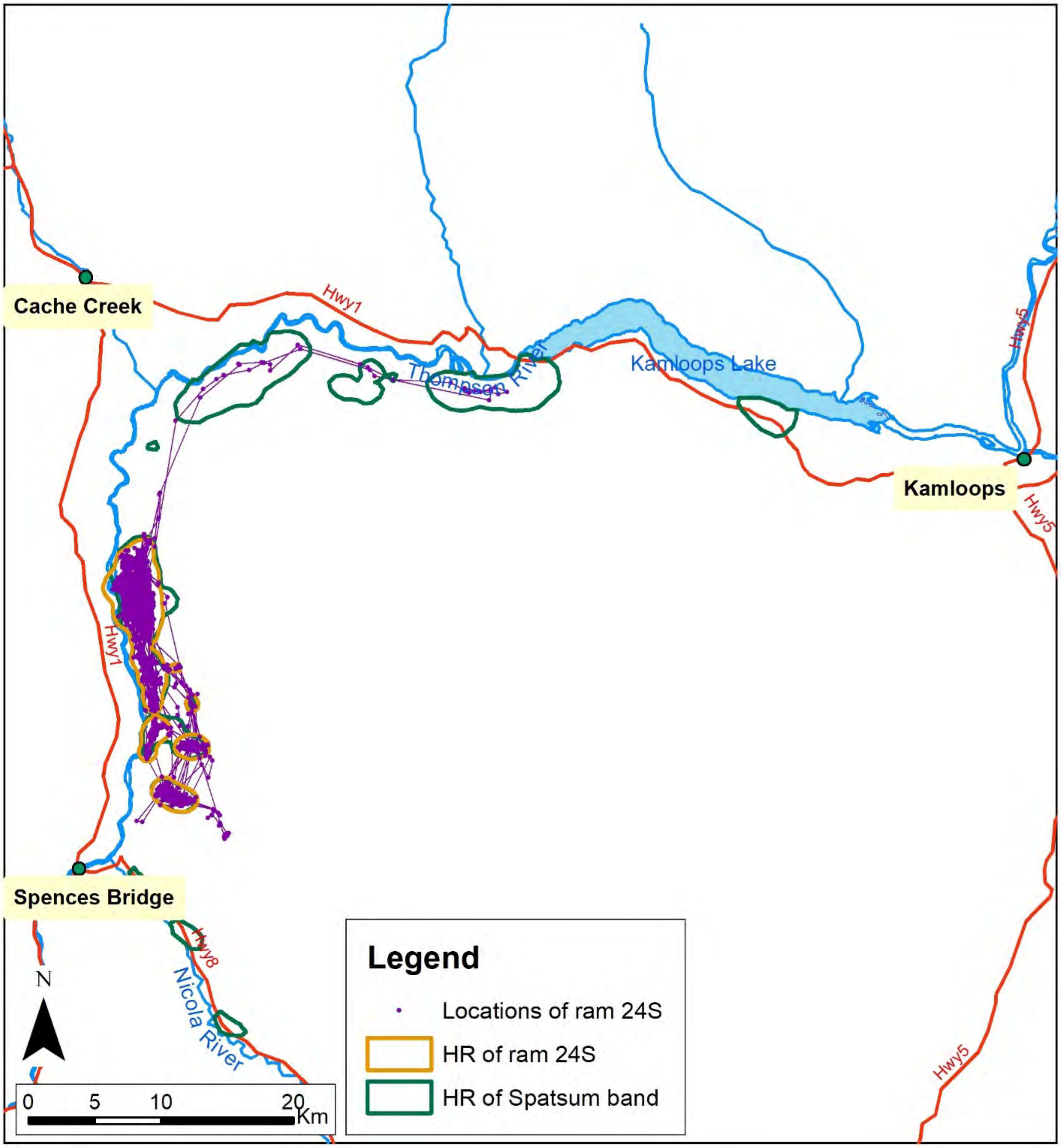

Fig. 3. 5: Example of foray movement of a single ram (ID: 24S) outfitted with a GPS collar from the Spatsum Bighorn Sheep ram band (Thompson Region, BC). The furthest distance this animal was detected out of its home range (orange contour) was 35.2 km. The foray movement overlaps with home range (HR) of another animals in the Spatsum band (green contour), and thus is not considered for the risk of contact assessment.

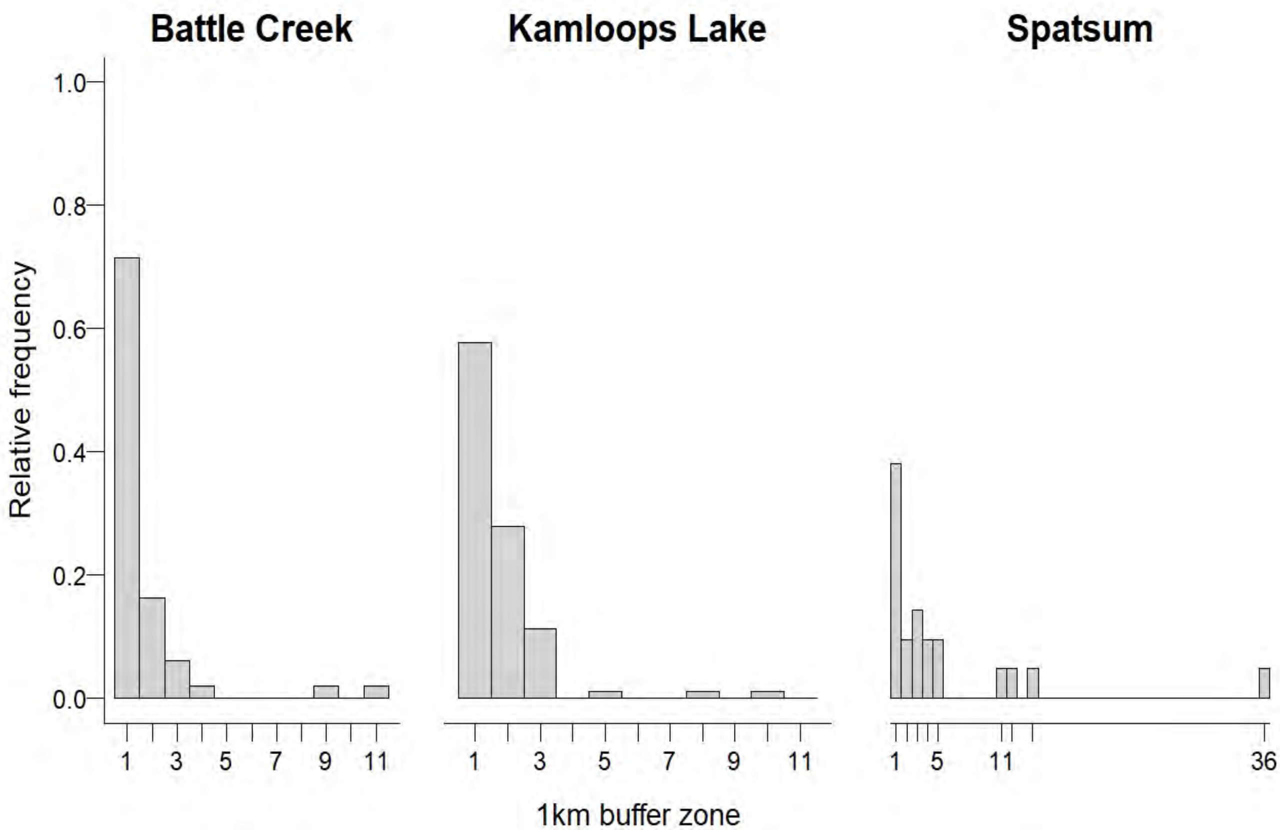

Fig. 3. 6: Distribution of distances (km) traveled on foray movements of three Bighorn Sheep bands. The traveled distance is measured from the nearest boundary of **individual ram's home range (HR)**. The y-axis represents proportion of forayaing rams that reach each 1-km-wide buffer zone along the x-axis. HR and foray movement distances are based on telemetry data collected from 38 rams from Thompson Region within the Central Interior of British Columbia (2015-2018).

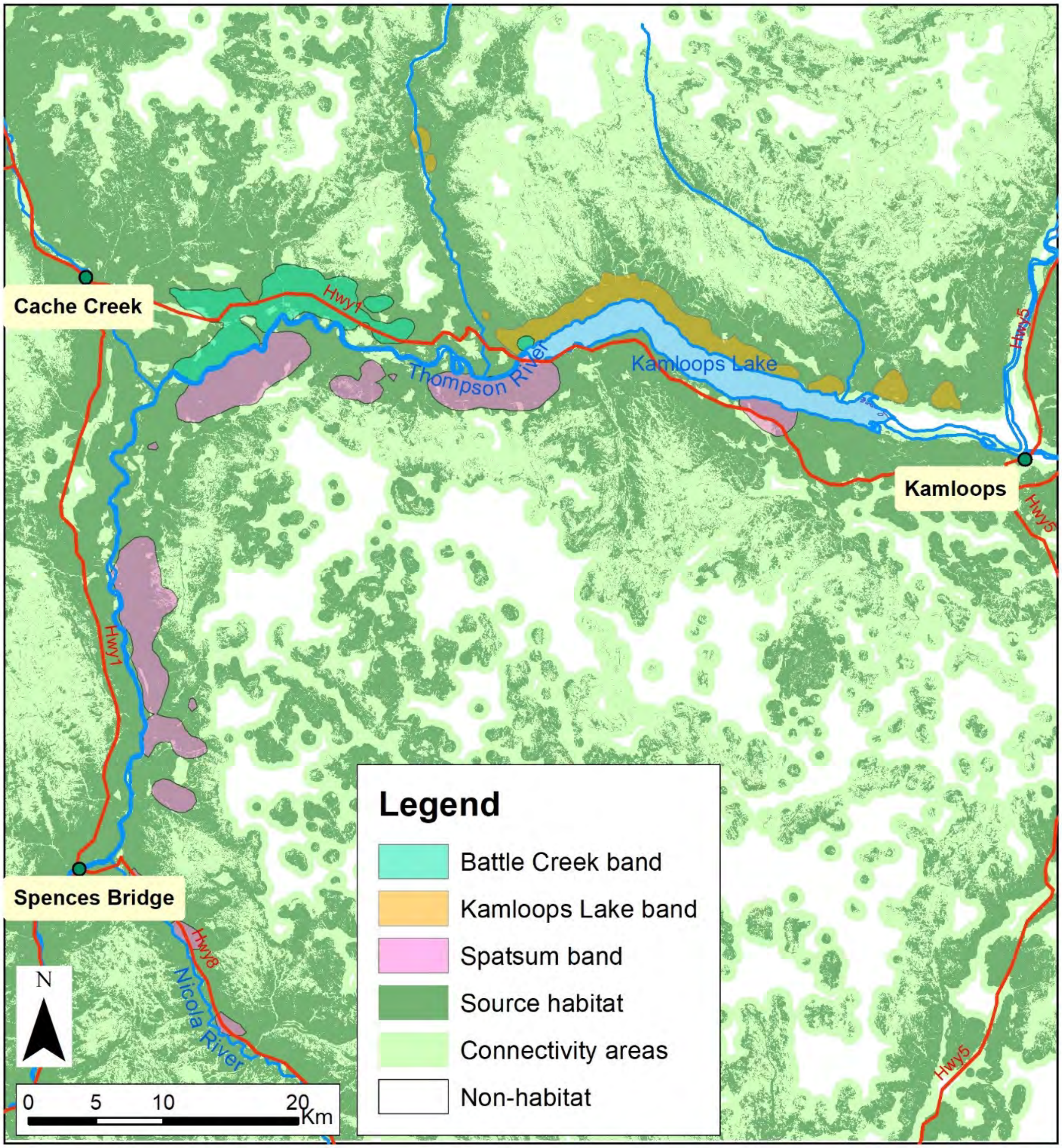

Fig. 3. 7: Map of the potential habitat and estimated home ranges (HR) of three Bighorn Sheep ram bands in Thompson Region within the Interior of British Columbia, Canada.

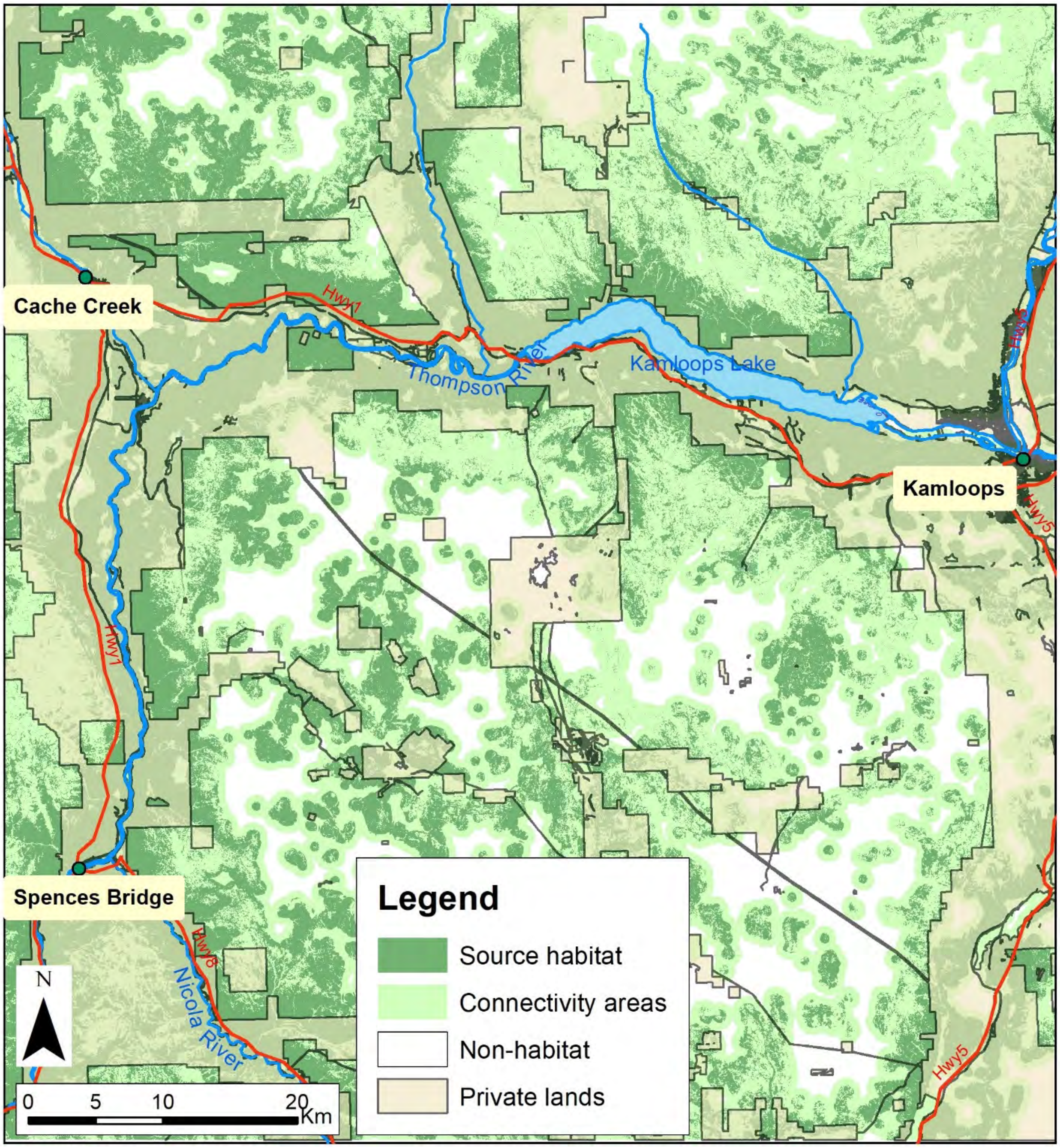

Fig. 3. 8: Map of the potential habitat and private land boundaries (as a crude approximation of grazing allotments) in the study of three Bighorn Sheep ram bands within the Thompson Region, BC, Canada.

half of it (47%) overlapping with bighorn source habitat (Table 3.3, Fig. 3.8). Overlaps between home ranges (HR) of all three bands and private parcels were relatively high (56% for Battle Creek band, 60% for Kamloops Lake band, and 71% for Spatsum band, Fig. 3.9).

Risk of Contact Tool (RoCT)

The RoCT estimates the probability that foraying bighorn will come in contact with a private parcel rather than with an individual domestic animal, as data were are not available to determine precise spatial or temporal use of domestic animals within study area. If grazing allotment (in this specific case: private parcel) intersected the bighorns HR, it is assumed that the probability of contact is 100% as the distance and permeability between bighorn HR and domestic sheep location largely determines the probability of contact. Figure 3.9 shows the foray probability as a gradient, with the highest probability near the overall HR, the probability decreases with the distance from the HR but also for the non-habitat areas. Individual bands Risk of Contact rasters are presented in Appendix 5. It should be also noted that the tool does not recognize natural barriers, some of these features may be significant for this study area.

Discussion

Contrary to results reported for bighorns elsewhere (Festa-Bianchet 1986, DeCesare and Pletscher 2006, O'Brien *et al.* 2014), rams in the studied area did not demonstrate long-distance forays outside of their HRs. More than half of the identified foray movements were short-distance and only one ram (out of 38) traveled more than 4 km beyond the bounds of its band' HR. Both of those factors (frequency and distance of forays) affect the risk of contact between foraying Bighorn Sheep (mostly rams) and domestic sheep, suggesting relatively lower levels of risk of occurrence. Two other factors affecting risk of contact are the availability of bighorn source habitat and the proximity of their HRs to domestic sheep. A significant percentage of private lands within the study area overlap with the modeled source habitat, as well as with all three estimated HR of the bighorn populations. Any areas of bighorns HR that overlaps with such private lands creates high risk of contact. In similar studies (US Rio Grande

Table 3. 3: Percent of overlap between home range (HR) or home range area with a 5km wide buffer zone (Buff5) for three Bighorn Sheep bands in Thompson Region of British Columbia, and the source habitat (see also Fig. 3.7), and private parcels (see also Fig. 3.9).

	Battle Creek (N=13)		**Kamloops Lake (N=11)**		**Spatsum (N=14)**	
	HR	**Buff5**	**HR**	**Buff5**	**HR**	**Buff5**
Source habitat	76.6%	42.9%	84.2%	33.5%	72.5%	36.9%
Private parcels	55.7%	59.8%	59.4%	52.5%	70.6%	49.9%

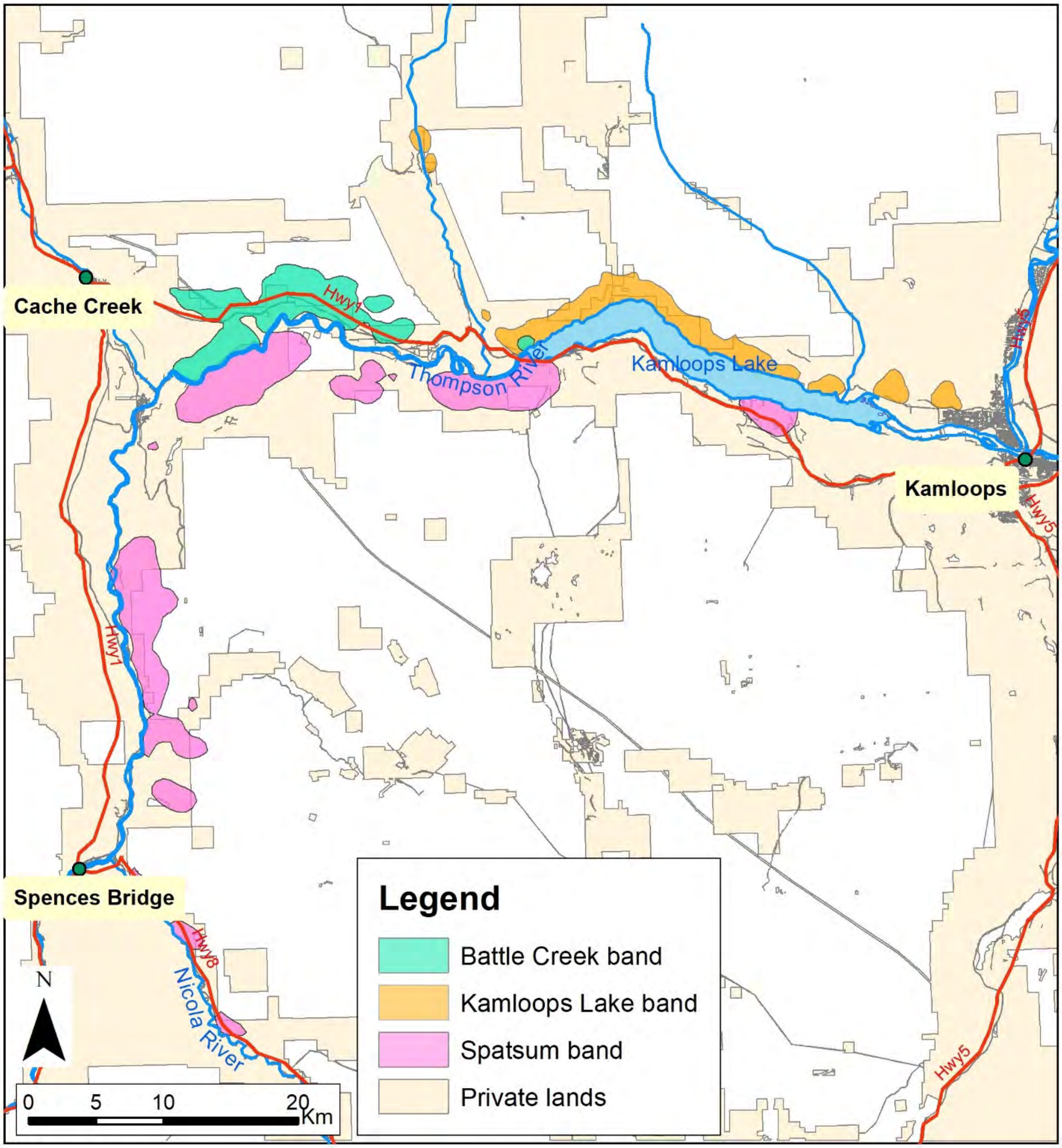

Fig. 3. 9: Map of the estimated home ranges (HR) of three Bighorn Sheep ram bands in relation to private lands in Thompson Region, BC, Canada.

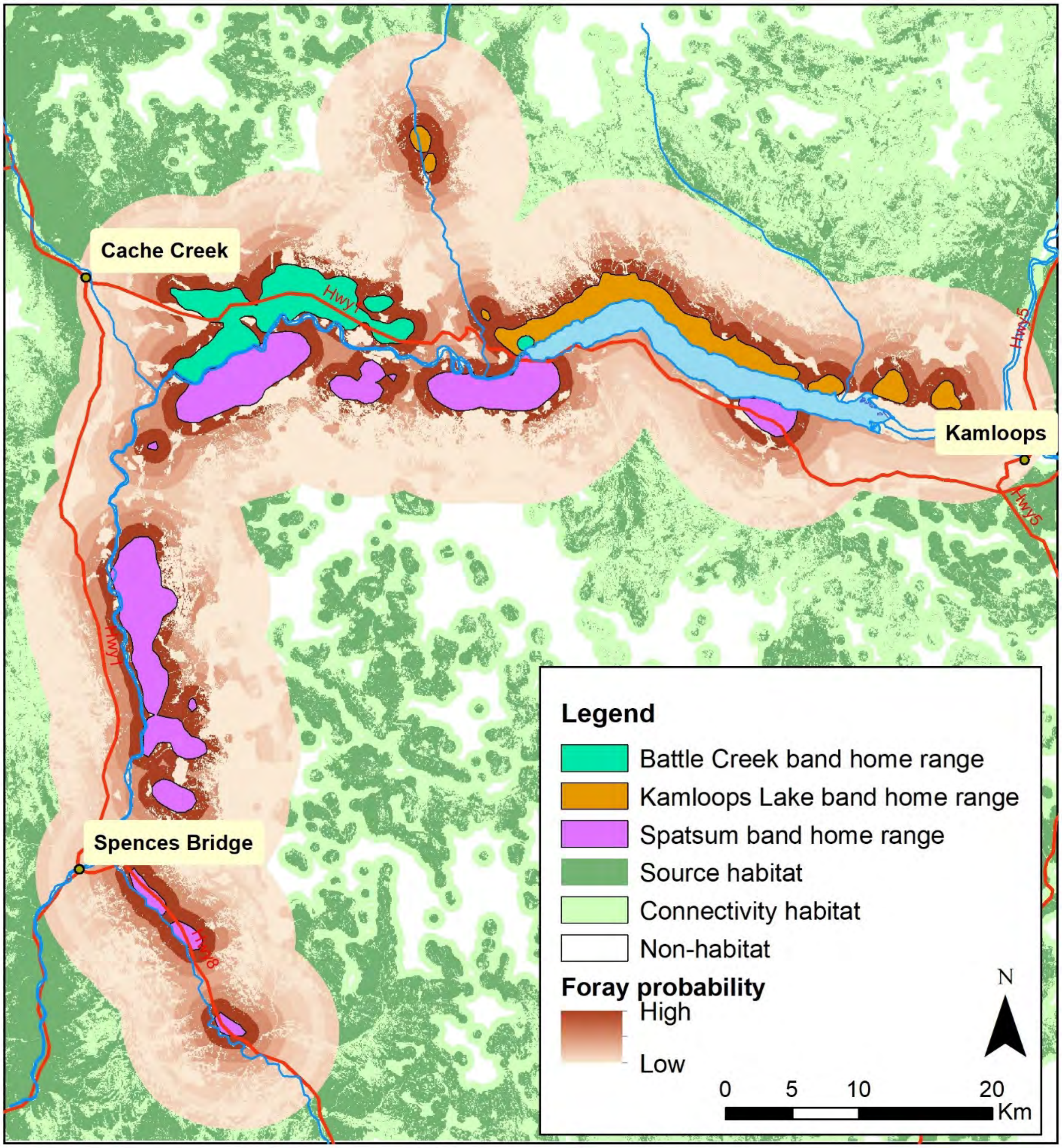

Fig. 3. 10: Foray probability raster generated in the Risk of Contact Tool for the three Bighorn Sheep ram bands in Thompson Region within the Interior of British Columbia, Canada. No recognition of natural barriers leads to portraying probabilities for not-accessible areas.

National Forest 2013; Carpenter *et al.* 2014; O'Brien *et al.* 2014; US Department of the Interior Bureau of Land Management 2019;) the researchers inferred 100% probability of interspecies contact when any single Bighorn Sheep HR overlapped with a domestic sheep allotment. In my study, 67% of the bighorns HRs overlap with private parcels which indicating that potential contact is and will remain a high risk for those bighorns.

Many researchers have advocated maintaining a separation zone (≥23 km) between domestic and Bighorn Sheep to reduce the risk of disease transmission (Gross, *et al.* 2000; Mack 2008; O'Brien *et al.* 2014; Porter and Sandborn 2014; Wild Sheep Working Group 2012). It is logistically difficult, if not impossible, to maintain such large separation zones in a landscape with multiple land uses, especially when the two species are closely related and thus have a tendency to mingle. Treatment or vaccination of free-ranging bighorn are not considered viable management options due to limited drug effectiveness and inherent logistical difficulties associated with delivering multiple doses of medication or vaccine in remote, inaccessible terrain (Cassirer *et al.* 2001; Ward *et al.* 1999). Another possibility could be vaccinating domestic sheep and creating *M.ovi*-free domestic sheep herds. In 2017 BC Wild Sheep Society launched a pilot program "Say NO to *M.ovi*" that works with domestic breeders and 4-H organizations to test flocks for *M.ovi* (BC Wild Sheep Society 2017). This process is moving slowly, as many sheep owners are hesitant to use antibiotics on their livestock. Unfortunately, even a failure to a small minority of livestock landowners to participate creates can have significant consequences. The precautionary principle thus suggests that domestic sheep farming should not occur within the known home ranges (and preferably the buffer zones) of Thompson Region Bighorn Sheep (i.e., create domestic sheep exclusion zones within home ranges and buffer zones of Thompson Bighorn Sheep).

Ninety-seven percent (97%) of the sheep location data points collected in this study fell within mapped source habitat, considerable greater than the minimum 75% recommended by Zeigenfuss *et al.* (2000) a result that validates the model. However, not all source habitat in my study area was occupied by collared Bighorn Sheep. This may be due to several reasons, including, but not limited to: (1) sheep populations are operating in this region well below carrying capacity (Chapter 2), (2) temporal distribution of nutritional forage creating pockets of unhealthy habitat, (3) exploration of the vacant habitat by transplanted Bighorn Sheep may not have occurred yet, (4) predator pressure, or (5) the model does not take into other key factors such as source habitat size and accessibility. Another possible reason could be a limited tendency of Bighorn Sheep to disperse and colonize unoccupied landscapes (Geist 1971, Singer *et al.* 2000, Jesmer *et al.* 2018). A lower propensity for foraying also could result from the sedentary nature of these herds (see Chapter 2), as translocated populations can be less migratory and thus also may be less prone to forays (Jesmer et al. 2018b; Lowrey et al. 2019). Translocation of animals into landscapes with low elevation diversity (no possibility to establish low-elevation winter ranges, high-elevation summer ranges, and seasonal migration routes) also could add to an already-slow generational process through which the animals accumulate their "knowledge" of the surrounding environment (Jesmer et al. 2018b; Lula et al. 2020).

Prior to this study, there was no record of a foray connection between the herds, but analysis of the positional data revealed three collared rams from Battle Creek band that forayed into the Kamloops Lake band HR. This represents a clear possibility of disease transmission risk between the two bands. Also locations of one ram from Spatsum band were found on the other side of Thompson River (approx. 15km south of Ashcroft, BC). This suggest possible disease transmission with neighbouring Spence's Bridge herd on the west side of Thompson River (that herd is part of the Fraser River metapopulation). Overall, these connections indicate high risk for wild sheep nearly in the entire Interior of BC. As foray movements often are omitted in movement analysis (generally recognized as outliers, O'Brien *et al.* 2014) this may underestimate the probability of contact with domestic sheep or overlook the areas where such contact is probable. Recognizing and distinguishing foray movements from non-foray movements will support land managers with more effective assessment of interspecies separation. As several other bighorn populations reside within the same region of BC, monitoring movements of those herds (followed by similar analysis) will help to prevent major consequences and better understand the risk of disease transmission between those herds.

The results from the RoCT provide a spatial map of risk of bighorns entering an allotment area, serving as a partial guide for resource decisions. It is a useful starting point for analysis, but insufficient as a stand-alone metric. The RoCT tool does not account for the movements of stray domestic animals coming into contact with Bighorn Sheep, as this risk is not solely based on movements of Bighorn Sheep. Other limitations, such as availability of data or topographical barriers that are not modeled should also be considered. But, as the RoCT tool is based on peer reviewed literature and has withstood legal challenges in Federal Court (USDA Forest Servies 2015), it provides a strong argument for the BC Sheep Separation Program (Government of British Columbia 2008) where contact between domestic and wild sheep is recognized as a management issue.

This study found significant implications in individual movement patterns of studied Bighorn Sheep. The importance of forayingi animals for movements and connectivity, particularly males, generally was not considered in the methods developed to date (often considered as outliers) and thus they may either underestimate the probability of contact with another animals, or overlook areas where such contact is possible. Distinguishing foray and non-foray movements, and relating them to source habitat models as a presentation of possible foray movement, provides land managers with a more appropriate tool for assessing the level of risk of contact between different groups of animals.

LITERATURE CITED

Advanced Telemetry Systems. 2013. ATS G2110E Iridium user manual.

Agricultural Land Commission (ALC). 2020. DataBC Program. Agricultural Land Reserve Lines. https://catalogue.data.gov.bc.ca/dataset/alc-agricultural-land-reserve-lines. Accessed 8 June 2020.

B.C. Conservation Data Centre. 2021. https://www2.gov.bc.ca/gov/content/environment/plants-animals-ecosystems/conservation- data-centre/explore-cdc-data/glossary-for-species-ecosystems-at-risk. Accessed 29 May 2021.

BC Ministry of Water Land and Air Protection. 2004. Bighorn Sheep (*Ovis Canadensis*) in Accounts and Measures for Managing Identified Wildlife. Accounts V. 2004, 19.

BC Wild Sheep Society. 2017. "Say NO to Movi" – Eating Movi off the Landscape. https://www.wildsheepsociety.com/say-no-movi-eating-movi-off-landscape/. Accessed 25 May 2021.

Bohonak, A. J. 1999. Dispersal, gene flow, and population structure. The Quarterly Review of Biology 4 (1).

Bowler, D. E., and T. G. Benton. 2005. Causes and consequences of animal dispersal strategies: relating individual behaviour to spatial dynamics. Biological Reviews of the Cambridge Philosophical Society 80 (2): 205–25.

Cagnacci, F., L. Boitani, R. A. Powell, and M. S. Boyce. 2010. Animal ecology meets GPS-based radiotelemetry: A perfect storm of opportunities and challenges. Philosophical Transactions of the Royal Society B: Biological Sciences 365 (1550): 2157–62.

Calenge, C, and S. Fortmann-Roe. 2017. Package 'AdehabitatHR.' *adehabitat*. CRAN.

Carpenter, T. E., V. L. Coggins, C. McCarthy, Ch. S. O'Brien, J. M. O'Brien, and T. J. Schommer. 2014. A spatial risk assessment of Bighorn Sheep extirpation by grazing domestic sheep on public lands. Preventive Veterinary Medicine 114 (1): 3–10.

Cassirer, F. E., K. M. Rudolph, P. Fowler, V. L. Coggins, D. L. Hunter, and M. W. Miller. 2001. Evaluation of ewe vaccination as a tool for increasing bighorn lamb survival following *Pasteurellosis* epizootics. Journal of Wildlife Diseases 37 (1): 49–57.

Dobson, S. F. 2013. The enduring question of sex-biased dispersal: Paul J. Greenwood's (1980) Seminal Contribution. Animal Behaviour 85 (2): 299–304.

European Space Agency. 2020. Sentinel-2. https://sentinel.esa.int/web/sentinel/missions/sentinel-2. Accessed 2 February 2020.

FS/BLM Bighorn Sheep Working Group. 2020. Bighorn Sheep Risk of Contact Tool user guide.

Geist, V. 1971. Mountain Sheep: A study in behavior and evolution. The Journal of Wildlife Management 36 (2): 673.

Getz, W. M., S. Fortmann-Roe, P. C. Cross, A. J. Lyons, S. J. Ryan, and Ch. C. Wilmers. 2007. LoCoH: nonparameteric kernel methods for constructing home ranges and Utilization Distributions. PLoS ONE 2 (2).

Government of British Columbia. 2021. The BC Sheep Separation Program. https://www2.gov.bc.ca/gov/content/environment/plants-animals-ecosystems/wildlife/wildlife-health/wildlife-health-matters/wild-sheep-health. Accessed 10 March 2021.

Gross, J. E., F. J. Singer, and M. E. Moses. 2000. Effects of disease, dispersal, and area on Bighorn Sheep restoration. Restoration Ecology 8 (4S): 25–37.

Gudorf, M., P. Sweanor, and F. Singer. 1996. Bighorn Sheep habitat assessment of the Greater Bighorn Canyon National Recreation Area. U.S. Department of Interior, National Biological Services, National Park Service.

Hells Canyon Bighorn Sheep Restoration Committee (HCBSRC). 1997. The Hells Canyon Initiative: Restoration of Bighorn Sheep to Hells Canyon. Idaho Department of Fish and Game, Oregon Department of Fish and Wildlife, Washington Department of Fish and Wildlife, U.S. Forest Service, Bureau of Land Management, Foundation for North American Wild Sheep, Idaho Department of Fish and Game, Lewiston, ID, USA.

Jesmer, B. R., J. A. Merkle, J. R. Goheen, E. O. Aikens, J. L. Beck, A. B. Courtemanch, M. A. Hurley. 2018. Is ungulate migration culturally transmitted? Evidence of social learning from translocated animals. Science 361 (6406): 1023–25.

Johnson, T. L., and D. M. Swift. 2000. A test of a habitat evaluation procedure for Rocky Mountain Bighorn Sheep. Restoration Ecology 8 (4S): 47–56.

Killeen, J., H. Thurfjell, S. Ciuti, D. Paton, M. Musiani, and M. S. Boyce. 2014. Habitat selection during ungulate dispersal and exploratory movement at broad and fine scale with implications for conservation management. Movement Ecology 2 (1): 1–13.

Lowrey, B., K.M. Proffitt, D.E. McWhirter, P.J. White, A.B. Courtemanch, S.R. Dewey, and H.M. Miyasaki. 2019. Characterizing population and individual Migration Patterns among Native and Restored Bighorn Sheep (*Ovis Canadensis*). Ecology and Evolution 9 (15): 8829–39.

Lula, E. S., B. Lowrey, K. M. Proffitt, A. R. Litt, J. A. Cunningham, C. J. Butler, and R. A. Garrott. 2020. Is habitat constraining Bighorn Sheep restoration? A case study. Journal of Wildlife Management 84 (3): 588–600.

Mack, C. M., M. Kasprzak, and K Luiz. 2017. Salmon River Bighorn Sheep Project - final report 2007-2015. Nez Perce Tribe, Lapwai, ID, USA.

Mack, C.M. 2008. Wandering Wild Sheep Policy: A Theoretical Review, 1–10. http://media.nwsgc.org/proceedings/NWSGC-2008/WANDERING_BIGHORN_SHEEP_6-25-09.pdf.

McComb, K., G. Shannon, S. M. Durant, K. Sayialel, R. Slotow, and J. Poole. 2011. Leadership in elephants: the adaptive value of age. Proceedings of the Royal Society B: Biological Sciences, 278: 3270-3276.

Mertes, K., J. A. Stabach, M. Songer, T. Wacher, J. Newby, J. Chuven, S. Al Dhaheri, P. Leimgruber, and S. Monfort. 2019. Management background and release conditions structure post-release movements in reintroduced ungulates. Frontiers in Ecology and Evolution 7 (December).

Ministry of Citizen Services. 2020. DataBC Program, ParcelMap BC Parcel Fabric. https://catalogue.data.gov.bc.ca/dataset/parcelmap-bc-parcel-fabric. Accessed 8 June 2020.

Ministry of Forest, Lands, Natural Resource Operations and Rural Development (FLNRORD). 2019. DataBC Program. BC Wild Mountain Sheep Registry. https://catalogue.data.gov.bc.ca/dataset/bc-wild-mountain-sheep-registry-distribution.

Accessed 4 November 2020.

O'Brien, J. M., Ch. S. O'Brien, C. McCarthy, and T. E. Carpenter. 2014. Incorporating foray behavior into models estimating contact risk between Bighorn Sheep and areas occupied by Domestic Sheep. Wildlife Society Bulletin 38 (2): 321–31.

Payette National Forest. 2010. Appendix M: Occupancy, risk, and the potential for contact report. https://www.fs.usda.gov/detailfull/payette/landmanagement/planning/?cid=FSM9_033278&width=full.

Porter, H., and C. Sandborn. 2014. Bighorn Sheep herd die-offs in British Columbia : The need for a provincial Wild/Domestic Sheep separation strategy. Environmental Law Centre, University of Victoria, Victoria, BC. http://www.elc.uvic.ca/wordpress/wp-content/uploads/2016/04/BighornSheep.pdf.

R Core Team. 2020. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org.

Sappington, M. J., K. M. Longshore, and D. B. Thompson. 2007. Quantifying landscape ruggedness for animal habitat analysis: A case study using Bighorn Sheep in the Mojave Desert. Journal of Wildlife Management 71 (5): 1419-26.

Schirokauer, D. 1996. The effects of 55 years of vegetative change on Bighorn Sheep habitat in the Sun River Area of Montana. MS thesis, University of Montana, Missoula, MT, USA.

Shackleton, D. M., C. C. Shank, and B. M. Wikeem. 1999. Natural history of Rocky Mountain and California Bighorn Sheep. Pages 78–138 *in* Mountain sheep of North America. University of Arizona Press, Tucson, USA.

Singer, F. J., Ch. M. Papouchis, and K. K. Symonds. 2000. Translocations as a tool for restoring populations of Bighorn Sheep. Restoration Ecology 8 (4S): 6–13.

Singer, F. J., L. C. Zeigenfuss, and L. Spicer. 2001. Role of patch size, disease, and movement in rapid extinction of Bighorn Sheep. Conservation Biology 15 (5): 1347–54.

Singer, F. J., V. C. Bleich, and M. A. Gudorf. 2000. Restoration of Bighorn Sheep metapopulations in and near Western National Parks. Restoration Ecology 8 (4 SUPPL): 14–24.

Smith, T. S, and D. S Winn. 1991. Habitat evaluation procedure for Rocky Mountain Bighorn Sheep in the Intermountain West. Great Basin Naturalist 51 (3): 21.

Statistics Canada. 2020. Table 32-10-0425-01. Sheep and lambs on census day. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210042501. Accessed 25 October 2020.

US Department of the Interior Bureau of Land Management. 2019. Modeling the probability of Bighorn Sheep association with Domestic Sheep and Goats. https://eplanning.blm.gov/

public_projects/lup/39877/174673/212671/Mod_Prob_BH_Assoc---Draft_ECRMP_supplement.pdf.

US Rio Grande National Forest. 2013. Risk of contact analysis between Bighorn and Domestic Sheep on the Fisher-Ivy / Goose Lake Domestic Sheep Grazing Allotment. Rio Grande National Forest Divide Ranger District. https://www.fs.usda.gov/nfs/11558/www/nepa/62975_FSPLT3_1422868.pdf.

USDA Forest Service. 2005. Decision for Appeal of the Payette National Forest Land and Resource Management Plan Revision, Washington, DC: USDA Forest Service, Washington Office. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fsm9_033078.pdf.

USDA Forest Services. 2015. Risk of Contact Tool, A quantitative means of assessing the probability of contact between bighorn sheep and grazing allotments. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd513118.pdf .

Ward, A.C.S., D.L. Hunter, K.M. Rudolph, W. J. DeLong, J. M. Bulgin, L. M. Cowan, H. J. McNeil, and M. W. Miller. 1999. Immunologic responses of Domestic and Bighorn Sheep to a multivalent *Pasteurella Haemolytica* Vaccine. Journal of Wildlife Diseases 35 (2): 285–96.

Wild Sheep Working Group. 2012. Recommendations for Domestic Sheep and Goat management in wild sheep habitat. https://wafwa.org/wpdm-package/recommendations-for-domestic-sheep-and-goat-management-in-wild-sheep-habitat-2/

Worton, B. J. 1989. Kernel methods for estimating the utilization distribution in home-range studies. Ecology 70 (1): 164–68.

Zeigenfuss, L. C., F. J. Singer, and M. A. Gudorf. 2000. Test of a modified habitat suitability model for Bighorn Sheep. Restoration Ecology 8 (4S): 38–46.

Personal Communications:

Ayotte, Jeremy, RPBio, 2021, Phyla Biological Consulting, Salmon Arm, British Columbia

Hales, Gerad, RPBio, 2021, Wildlife Management Specialist, British Columbia Ministry of Forests Lands, Natural Resource Operations and Rural Development (BC FLNRORD), Kamloops, British Columbia.

Iredale, Francis J., RPBio, 2021, Wildlife Biologist, British Columbia Ministry of Forests Lands, Natural Resource Operations and Rural Development (BC FLNRORD), Kamloops, British Columbia.

Procter, Chris, RPBio, 2021, Wildlife Biologist, British Columbia Ministry of Forests Lands, Natural Resource Operations and Rural Development (BC FLNRORD), Kamloops, British Columbia.

Chapter Four: Conclusions and Management Recommendations

Main conclusions

This study provides insight into how Bighorn Sheep in the study region distribute themselves across the landscape, how this distribution changes with season, and how this distribution relates to potential interactions with other groups of bighorns and domestic sheep. All of these elements are critical for gaining insight into key aspects of the species' ecology, such as habitat preferences, carrying capacity, or identifying risk of disease transmission. Thus, the primary goals of my study of several herds of Bighorn Sheep in the Thompson Region within the Interior of British Columbia were:

1. to estimate home ranges, core areas, and seasonal ranges of the studied animals while using four different estimation methods to produce the most justifiable result,
2. to define migration/movement patterns and look for connectivity between herds and their seasonal ranges,
3. to extract and analyze foray movements as a potential vector of disease transmission, and
4. to develop a source habitat model as a tool to identify risk of contact with domestic sheep or goats.

1. Range analysis

The size and shape of home ranges often are used as a guide to define the scale of management, as well as to determine habitat preference and subsequent habitat suitability (Chetkiewicz and Boyce 2009; Lu *et al*. 2012). I evaluated the home ranges and the core areas using four estimation methods. The main points were as follows:

- each estimation method provided relatively different shapes and areas for a band's home range; thus, an expert opinion and the intended use of the estimated home range should inform the selection of the most appropriate estimation method, and

- despite providing relatively smaller estimates of a band's home range, the Local Convex Hull (LoCoH) method most accurately recognized natural barriers that significantly constrain animal movements in the study area, a strong argument for its selection.

This work, however, does not identify a method that is preferable for this type of study, but rather, it has shown that the method of home range estimation, when used to estimate the areas of habitat used by a species, may have a significant effect on the results. For example, if the goal of home range study is to determine the extent of land to be preserved for conservation of a species, it is crucial to determine that amount without underestimating its spatial needs or inflating the area that would be workable to preserve. An estimation method that provides the option of an adjustable buffer zone (e.g. kernel-based methods) around the detected location points would be better suited for this application.

2. Connectivity and seasonal movements analysis

The estimated home ranges of the two neighboring bands (Battle Creek and Kamloops Lake bands, see Fig 3.2, or Fig. 3.7, or Fig. 3.9) overlapped suggesting existing continuous connections between those two sub-populations, but no such overlap was seen for the third band (Spatsum). However one ram from Spatsum band cross the Thompson River (approx. 15km south of Ashcroft, BC), thus connecting it to the Spence's Bridge herd, and likely the rest of the Fraser River metapopulation. Here are the three key points to come out of my study in this regard:

- the detected connectivity between the two bands (Battle Creek and Kamloops Lake) provides opportunities for gene flow, as well as disease transmission,
- the lack of connectivity of these two bands with the third band (Spatsum) provides some protection from the spreading of disease, but it may also prevent gene flow and outbreeding; however the connectivity of the Spatsum band with the Spence's Bridge herd (not included in this study) creates the risk of possible disease spread throughout the Fraser River metapopulation. A similar situation may involve the Battle Creek and Kamloops Lake herds, and

- the high degree of overlap between the seasonal home ranges of each band suggests non-migratory latitudinal movements and sedentariness.

My findings agree with recent studies (Jesmer *et al.* 2018; Lowrey *et al.* 2019; Lula *et al.* 2020) that showed lower migration variability in restored Bighorn Sheep populations. Considerably more time (i.e. centuries) may be required for such restored populations to develop their 'knowledge' of the surrounding available habitat, leading to migratory behaviour (Jesmer *et al.* 2018). However, non-migratory behaviour often is considered a normal life-history strategy for California bighorns in the Interior of BC (Procter, pers. comm., FLNRORD). Such non-migratory populations are more likely to be impacted through various demographic mechanisms (i.e. range overgrazing, inbreeding depression). Thus local conservation efforts should be focused on mitigating those possible circumstances.

3. Foray movements analysis

The foray movements by bighorn generally are considered as outliers and often ignored in analysis (O'Brien *et al.* 2014), thus possibly underestimating the probability of contact with domestic sheep. In contrast to Bighorn Sheep forays reported elsewhere (Festa-Bianchet 1986; DeCesare and Pletscher 2006; O'Brien *et al.* 2014), the rams in this study exhibited relatively philopatric (<6km) foray movements, suggesting a relatively low level of risk-of-contact with domestic sheep in the area. However, three important considerations must be made here:

- a significant proportion of private land with agriculture status overlaps or lies adjacent to the home ranges of the herds in this study,
- there is a lack of a provincial spatial database identifying domestic sheep operations, much less their range use, and
- 80% of private lands bordering on the ranges used by the bighorn herds have agriculture capability, and thus there are no current restrictions on harbouring domestic livestock (especially on domestic sheep, goats, and llamas).

Taken together, the above suggests that significant risk exists for contact between domestic and Bighorn Sheep.

4. Source habitat and risk of contact with domestic animals

The source habitat model developed in this work classified 42% of the study area as potential source habitat for Bighorn Sheep, whereas the home range models estimated that only 9.2% of that habitat currently is occupied by the animals monitored in this study. As the source habitat had high overlap (97%) with locations of collared animals, it seems likely that it is representative of habitat used by uncollared rams of the herds. Further study would be needed to confirm this statement.

Bighorn Sheep generally exhibit a limited willingness to disperse and colonize unoccupied landscapes (Geist 1972; Bleich et al. 1994; Jesmer et al. 2018a), and when dispersal occurs, it is typically into contiguous habitat already occupied by other Bighorn Sheep (Geist 1972; Bleich *et al.* 1994). Others (Jesmer *et al.* 2018; Singer *et al.* 2000; Lowrey *et al.* 2019; Lula *et al.* 2020) have reported that gregarious social system and familiarity with traditional home ranges and migration routes from older members of the herd limits the possible expansion of Bighorn Sheep populations into unoccupied, yet suitable, habitat.

The Risk of Contact Tool provides wildlife managers and policy makers with a strong argument to prioritize Bighorn Sheep conservation over domestic sheep farming in high-risk areas. Resources can be focused on those areas designated as highest risk, increasing the likelihood of positive action. Indeed, the tool should provide a point for discussing management options for the BC Sheep Separation Program (Government of British Columbia 2008). A similar policy recently was established in the Yukon (Sheep and Goat Control Order - Government of Yukon 2020) under the Animal Health Act. The aim is to reduce risk of wild Thinhorn Sheep (*Ovis dalli*) and Mountain Goat (*Oreamnos americanus*) exposure to pathogens, especially *Mycoplasma ovipneumoniae* (*M.ovi)* that can be carried by healthy domestic sheep or goats. The order affords protection from disease transmission by separating domesticated populations from wild ones. It came into effect on January 1, 2020 and requires all owners of sheep and goats in Yukon to comply with the order through fencing and testing.

Limitations and future study

All telemetry studies ultimately are limited in the number of animals that may be simultaneously tracked, and this study was no exception. A much larger and more costly study would have been required to track ewes as well as rams. In general, my ability to draw comparisons with other studies were somewhat limited by the absence of data on ewe movements. Ewes also are known to conduct foray movements, albeit reported to be less frequent and shorter in distance (Carpenter *et al.* 2014). Still, a future assessment of ewe movement patterns and home ranges would be valuable. Overall, this study monitored relatively small proportions of animals in each herd (Battle Creek: 14 out of 120 estimated sheep, Kamloops Lake: 11 out of 210 estimated sheep, Spatsum: 14 out of 195 estimated sheep, BC FLNRORD unpubl. 2018), thus suggesting connectivity and risk of disease spread between the focal and neighbouring herds may be under-estimated.

Although this project was successful in collaring more rams than originally intended (40 instead of 33), it should be noted that this was possible, in part, because 8 (20%) of the rams collared died from anthropogenic causes (7 due to vehicular collisions, and 1 due to hunting), and 4 (10%) by predation (e.g. cougars). As well, several collars either prematurely released from their animals, or malfunctioned, resulting in a loss of data acquisition [eight collars (20%) acquired data for less than half a year with two collars (7.5%) for less than a month]. However, the retrieval, refurbishment and redeployment of some of these collars has allowed the collaring of more rams than originally intended, while remaining within project budget.

Management recommendations:

Given the major outcomes of this study, I make the following recommendations for the continued management of the Bighorn Sheep in this region:

- Implement a Domestic Sheep Exclusion Zone in high-risk areas (defined by the Risk of Contact Tool) as an effective means of separate wild and domestic sheep and goats, thus ensuring healthy wild sheep populations in the long-term and the sustainability of hunting and commercial opportunities in the region. Research is ongoing but it is widely recognized that there are no current effective treatments or preventative measures other than physical separation from domestic sheep and goats. Based on recent work (Procter, Pers. comm., FLNRORD), the cost to treat *M.ovi* infection is about $1500-1800 per sheep, making it a costly endeavor. A priority needs to be given to one species over the other.

- A collaring project focused on ewes from the studied herds would provide valuable information on the home ranges, movement patterns and in the mitigation of risk once *M.ovi* is present.
- Registering and inventory of farms rearing livestock such as domestic sheep, goats, and llamas. Currently there is no registration required and no inventory of the spatial or temporal distribution of these animals in the province. Given the severity of Bighorn Sheep respiratory die-offs and the role of domestic sheep as a causal factor, accurate assessments of domestic sheep farms are necessary to begin minimizing contact between Bighorn Sheep and the domestic species. Education programs with incentives or regulations to discourage farmers from maintaining domestic sheep in areas close to Bighorn Sheep habitat may reduce this risk.
- A significant number (18%) of collared rams died in vehicular collisions suggesting the need to improve uninterrupted connections between fragmented sheep habitat. It could be obtained through reducing traffic speed, additional signage, or a wildlife overpass.
- Conduct habitat enhancement (by thinning and/or fire prescriptions) as a way to keep Bighorn Sheep away from private lands. Focusing on areas immediately adjacent to occupied habitat and emphasizing treatment of areas within or near escape terrain.

I also would highly recommend a public education and awareness program that conveys the importance of Bighorn Sheep to the biodiversity of British Columbia. Information posters in established viewing areas could outline the importance of the Thompson Region herds to the North American Bighorn Sheep population as well as the potential negative effects of human activity. Education programs and promotional materials could connect different stakeholders and raise awareness and appreciation for this iconic species and thus provide public support for conservation actions.

Conclusions

The outcomes of my work are beneficial for bighorn management at the local and global level. At the local level, I have increased our understanding of the home ranges and movement patterns of bighorn ram bands. I have demonstrated connections between at least two focal herds and between them and a larger, additional metapopulation of sheep. Also, I have related my results to the risk of disease transmission from domestic sheep. More broadly, the approaches I have taken herein may be applied to other bighorn herds (modeling source habitat, detecting foray movements, defining high-risk areas through Risk of Contact Tool). All in all, my thesis contributes information to help delineate management options for maintaining healthy Bighorn Sheep herds. A collaborative management approach involving local communities alongside continued monitoring of the herds are key to ensure viable sheep populations resilient to immediate and future threats.

Literature Cited

Ayotte, J. 2020. Chasm bighorns: 2019-2020 selective removal trial, progress report. Wild Sheep Society of BC. https://www.wildsheepsociety.com/wp-content/uploads/2020/07/2020-Chasm-Test-and-Remove-Progress-Report-WSSOBC.pdf

Bleich, V. C., J. D. Wehausen, R. R. Ramey II, and J. L. Rechel. 1994. Metapopulation theory and Mountain Sheep: Implications for conservation. *In* Metapopulations and Wildlife Conservation, 353–73. Island Press, Covelo, CA, USA.

Carpenter, T. E., V. L. Coggins, C. McCarthy, Ch. S. O’Brien, J. M. O’Brien, and T. J. Schommer. 2014. A spatial risk assessment of Bighorn Sheep extirpation by grazing Domestic Sheep on public lands. Preventive Veterinary Medicine, 114 (1): 3–10.

Chetkiewicz, Ch. L., and M. S. Boyce. 2009. Use of resource selection functions to identify conservation corridors. Journal of Applied Ecology, 46 (5): 1036–47.

DeCesare, N. J., and D. H. Pletscher. 2006. Movements, connectivity, and resource selection of Rocky Mountain Bighorn Sheep. Journal of Mammalogy, 87 (3): 531–38.

Festa-Bianchet, M. 1986. Site Fidelity and Seasonal Range Use by Bighorn Rams. Canadian Journal of Zoology, 64 (10): 2126–32.

France, T. L. 2015. Behaviour, gastrointestinal parasites, and stress hormones of the South Thompson California Bighorn Sheep (*Ovis canadensis*). MSc thesis. Thompson Rivers University, Kamloops, BC, Canada.

Geist, V. 1972. Mountain Sheep: A study in behavior and evolution. The Journal of Wildlife Management, 36 (2): 673.

Government of British Columbia. 2021. The BC Sheep Separation Program. https://www2.gov.bc.ca/gov/content/environment/plants-animals-ecosystems/wildlife/wildlife-health/wildlife-health-matters/wild-sheep-health. Accessed 10 March 2021.

Government of Yukon. 2020. Sheep and goat control order. https://yukon.ca/sites/yukon.ca/files/emr-sheep-goat-control-order-fact-sheet.pdf. Accessed 11 April 2021.

Jesmer, B. R., J. A. Merkle, J. R. Goheen, E. O. Aikens, J. L. Beck, A. B. Courtemanch, and M. A. Hurley. 2018. Is ungulate migration culturally transmitted? Evidence of social learning from translocated animals. Science, 361 (6406): 1023–25.

Lowrey, B., K. M. Proffitt, D. E. McWhirter, P. J. White, A. B. Courtemanch, S. R. Dewey, and H. M. Miyasaki. 2019. Characterizing population and individual migration patterns among native and restored Bighorn Sheep (*Ovis canadensis*). Ecology and Evolution, 9 (15): 8829–39.

Lu, N., Ch. Xi Jia, H. Lloyd, and Y. Hua Sun. 2012. Species-specific habitat fragmentation assessment, considering the ecological niche requirements and dispersal capability. Biological Conservation, 152: 102–9.

Lula, E. S., B. Lowrey, K. M. Proffitt, A. R. Litt, J. A. Cunningham, C. J. Butler, and R. A. Garrott. 2020. Is habitat constraining Bighorn Sheep restoration? A case study. Journal of Wildlife Management, 84 (3): 588–600.

O'Brien, J. M., Ch. S. O'Brien, C. McCarthy, and T. E. Carpenter. 2014. Incorporating foray behavior into models estimating contact risk between Bighorn Sheep and areas occupied by Domestic Sheep. Wildlife Society Bulletin, 38 (2): 321–31.

Singer, F. J., V. C. Bleich, and M. A. Gudorf. 2000. Restoration of Bighorn Sheep metapopulations in and near Western National Parks. Restoration Ecology, 8 (4 SUPPL): 14–24.

US Department of the Interior Bureau of Land Management. 2019. Modeling the probability of Bighorn Sheep association with Domestic Sheep and Goats. https://eplanning.blm.gov/public_projects/lup/39877/174673/212671/Mod_Prob_BH_Assoc---Draft_ECRMP_supplement.pdf

US Rio Grande National Forest. 2013. Risk of contact analysis between Bighorn and Domestic Sheep on the Fisher-Ivy / Goose Lake Domestic Sheep Grazing Allotment. https://www.fs.usda.gov/nfs/11558/www/nepa/62975_FSPLT3_1422868.pdf.

USDA Forest Services. 2015. Risk of Contact Tool, A quantitative means of assessing the probability of contact between Bighorn Sheep and grazing allotments. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd513118.pdf .

APPENDICES

APPENDIX 1:

Time chart of data locations of captured 40 rams with their wildlife identification number (WLH ID), time span of recorded locations, number of recording days, as well as number of recorded data-points.

Ram with capture number 11 from Kamloops Lake band, did not have a biological samples taken, thus did not received a WLH ID.

Five rams were excluded from seasonal home range calculations due to insufficient length of the data collection period. One from Battle Creek band (WLH ID: 16-8858), two from Chasm band (WLH ID: 15-6417, 15-6367), and two from Spatsum band (WLH ID: 15-6353, 16-8856).

Appendix 1

Capture No.	WLH ID	No. of days	No. of datapoint
Battle Creek rams (13)			
1	15-6358	650	3479
2	15-6356	1024	6017
5	15-6374	818	4853
6	15-6369	800	4742
15	15-6364	713	4235
16	15-6361	636	3773
20	15-6363	1074	6644
28	15-6372	868	5149
29	15-6414	412	2453
39	16-8848	96	581
40	16-8847	340	1991
41	16-8857	705	4382
42	16-8858	20	133
Chasm rams (2)			
21	15-6417	154	874
22	15-6367	81	443
Kamoops Lake rams (11)			
3	15-6359	1156	6906
4	15-6360	924	5517
10	15-6370	755	4505
11	~	915	5463
12	15-6350	1161	6948
13	15-6351	1201	7102
18	15-6354	677	4057
19	15-6355	516	3059
33	16-8853	707	4529
34	16-8851	707	4423
35	16-8855	706	4476
Spatzum rams (14)			
9	15-6357	439	2565
14	15-6352	930	5564
17	15-6353	35	130
23	15-6416	123	695
24	15-6362	776	4645
25	15-6371	138	839
26	15-6365	613	3622
27	15-6415	424	2553
30	15-6368	520	2871
31	16-8852	225	1197
32	16-8850	373	2254
36	16-8854	699	4161
37	16-8849	706	4230
38	16-8856	20	141
		total:	**142,201**

~ no biological sample taken during capture

data withouth software error

data with software error as of December 27, 2015.

APPENDIX 2

Home range (95% isopleth) and core range (50% isopleth) estimates of four Bighorn sheep (*Ovis canadensis*) ram bands in Thompson Region, British Columbia, Canada.

The data was collected as a part of Thompson Region Collaring Project lead by Ministry of Forest, Lands, Natural Resource Operations, and Rural Development. For the time span of collected data please refer to Appendix 1.

Basemaps were obtained through publicly available data from Sentinel-2 satellite (European Space Agency, 2020) and represent area visited on 12 June 2017.

The coordinates of the centers of each map are:

- Battle Creek area: 50°46'09.0"N 121°03'10.5"W
- Kamloops Lake area: 50°46'03.0"N 120°41'19.4"W
- Spatsum area: 50°30'22.4"N 120°56'14.9"W
- Chasm area: 51°00'47.5"N 121°22'21.6"W

Appendix 2

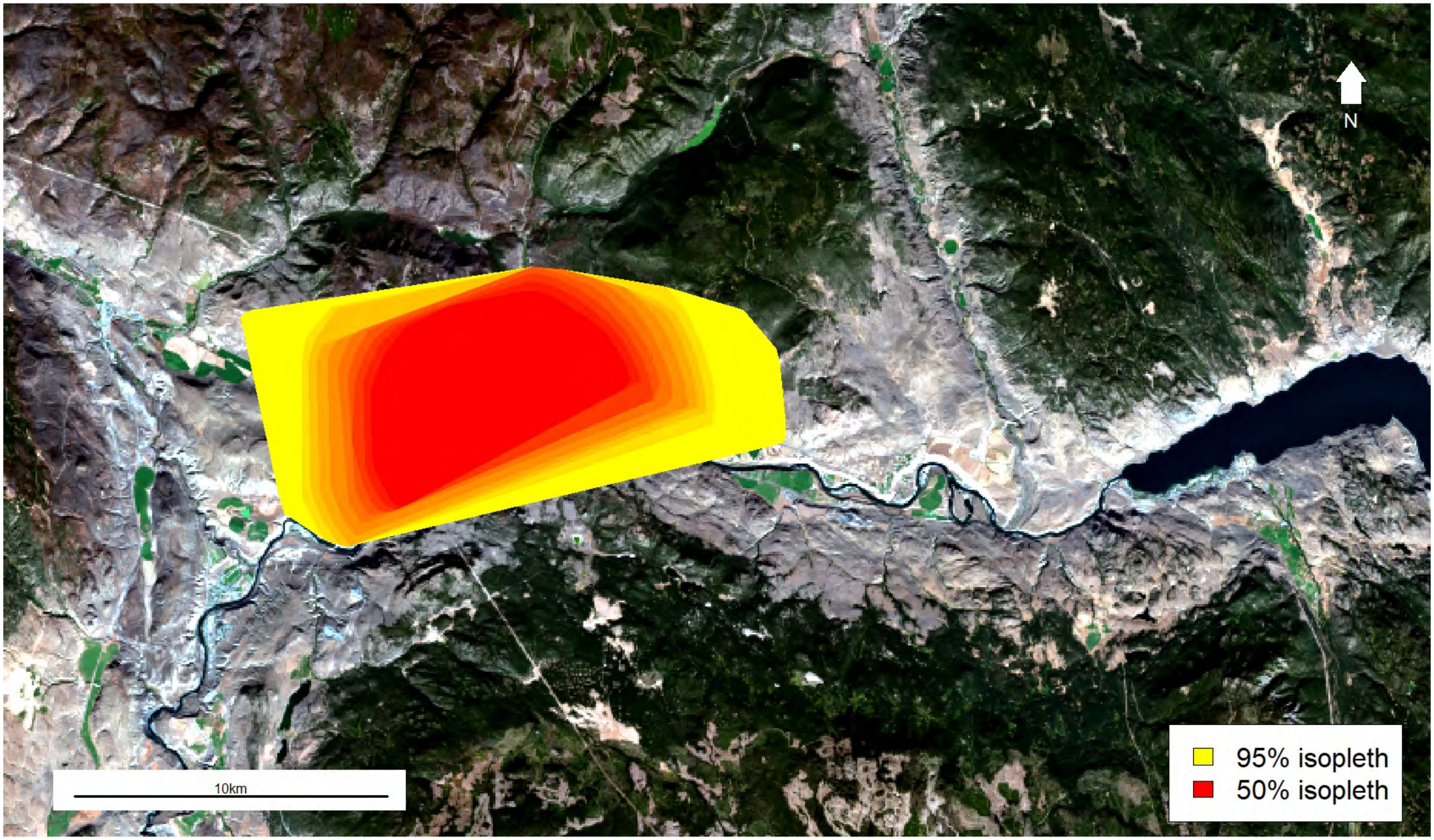

Fig.1a: Minimum Convex Polygon (MCP) map for the Battle Creek ram band; 95% isopleth covers 117.8km^2, 50% isopleth covers 35.9km^2;

Appendix 2

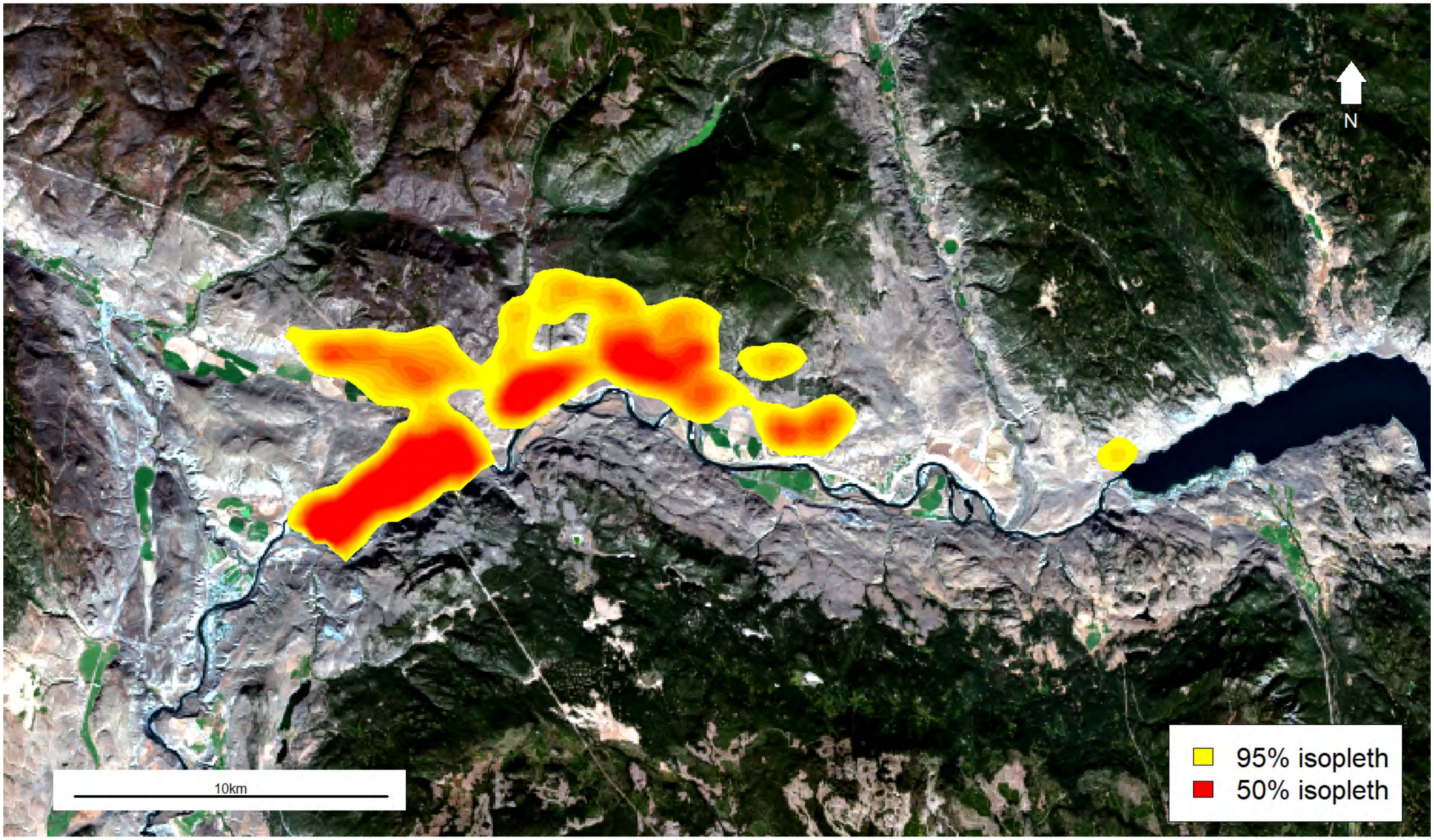

Fig.1b: Kernel density estimator (KDE) with plug-in smoothing parameter map for the Battle Creek ram band; 95% isopleth covers 61.5km^2, 50% isopleth covers 9.9km^2; the smoothing parameter h=321m;

Appendix 2

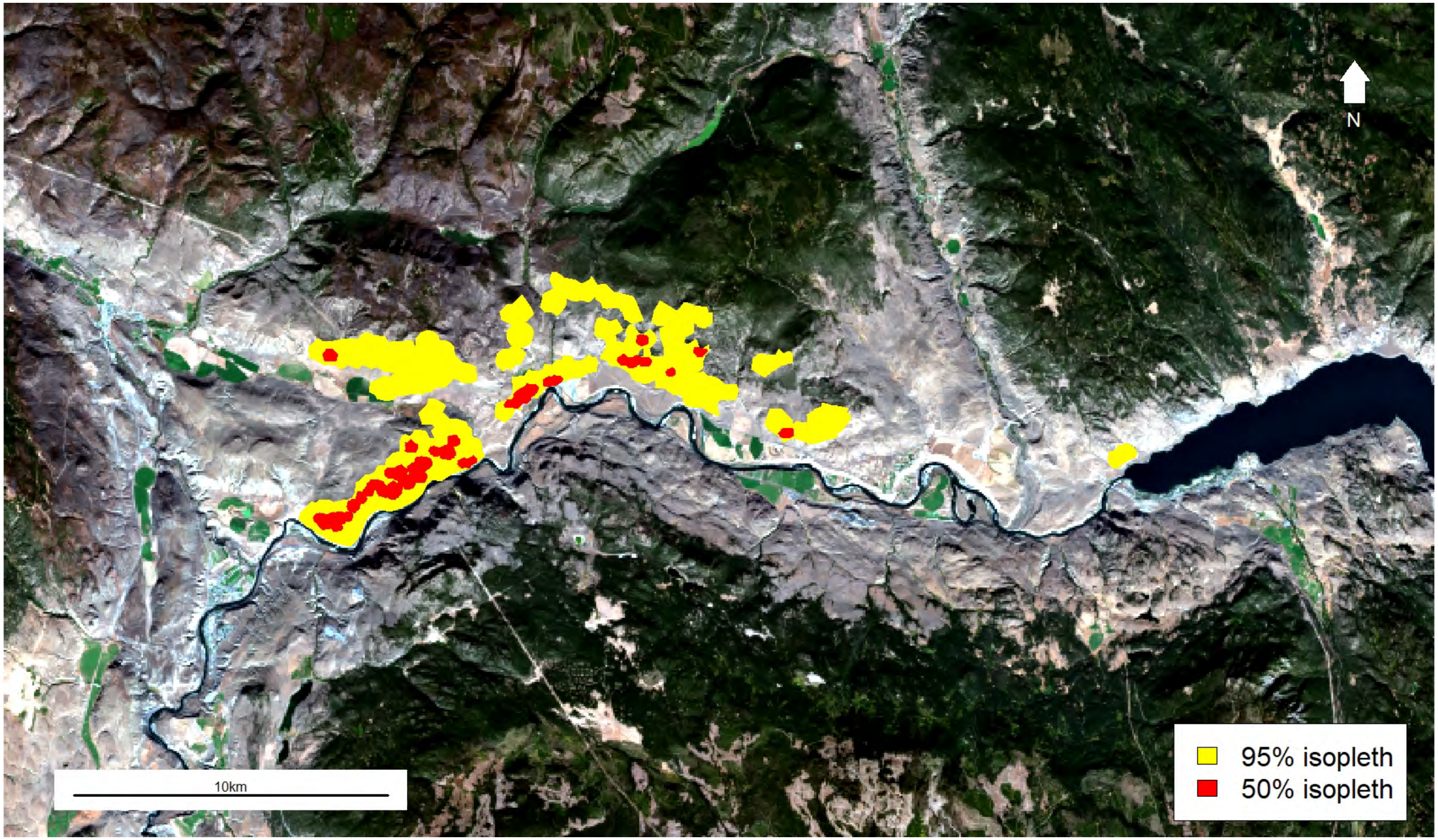

Fig.1c: Adaptive local convex hull (LoCoH) map for the Battle Creek ram band; 95% isopleth covers 30.0km^2, 50% isopleth covers 4.6km^2; the adaptive parameter a=31,298m;

Appendix 2

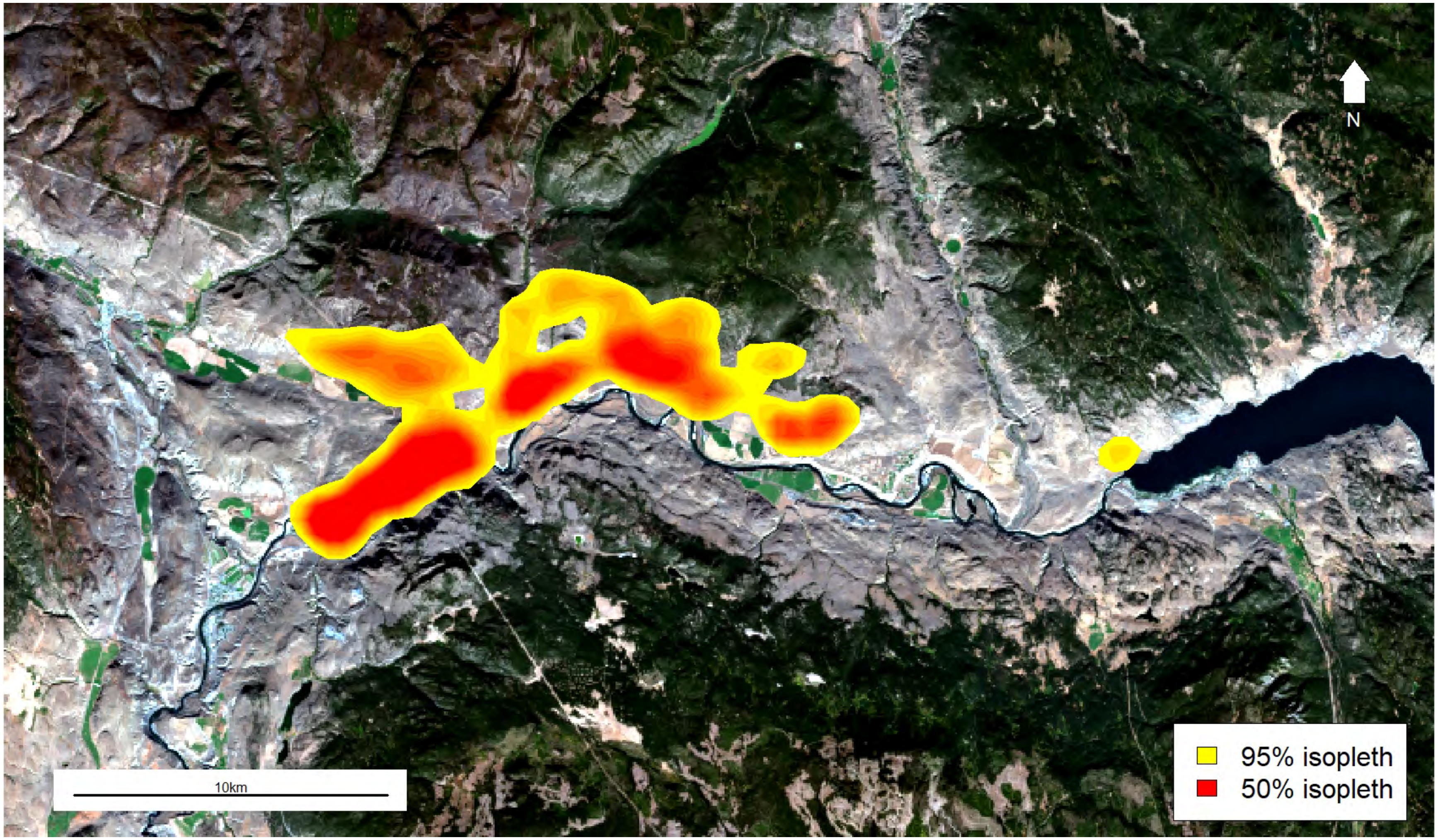

Fig.1d: Biased random bridge (BRB) map for the Battle Creek ram band; 95% isopleth covers 65.3km^2, 50% isopleth covers 9.9km^2; the upper recording time threshold was set to 4 hours;

Appendix 2

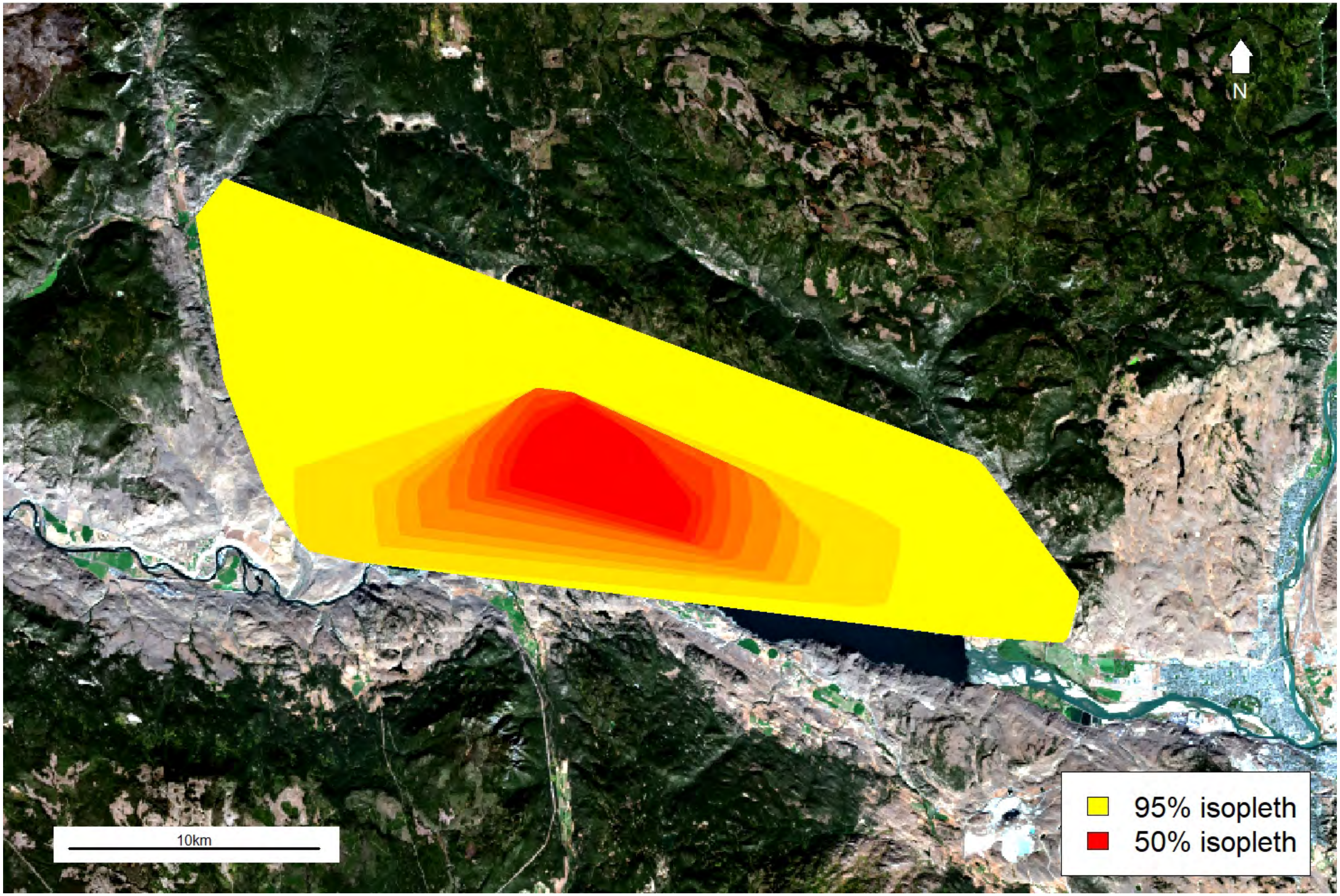

Fig.2a: Minimum Convex Polygon (MCP) map for the Kamloops Lake ram band; 95% isopleth covers 344.2km^2, 50% isopleth covers 21.4km^2;

Appendix 2

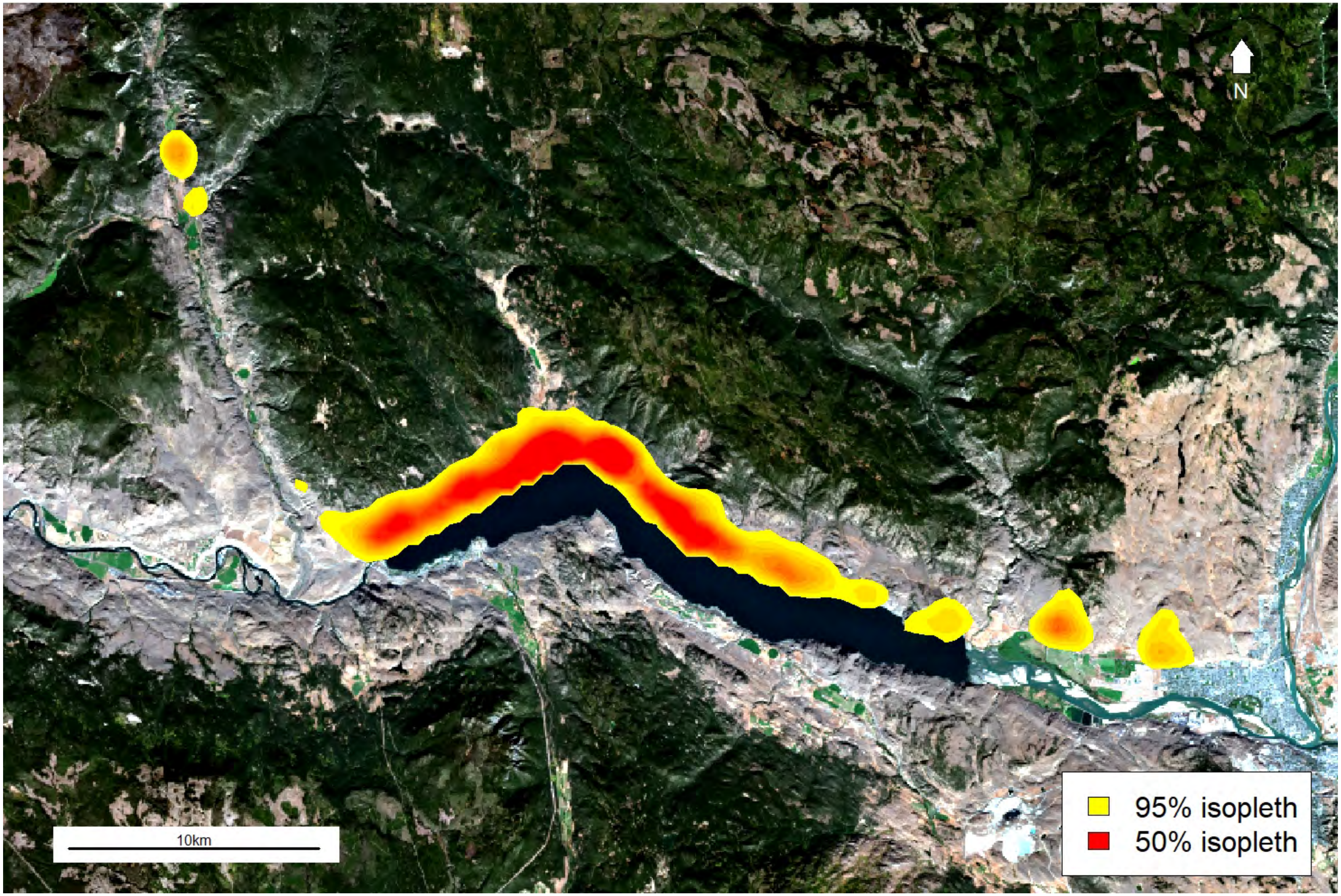

Fig.2b: Kernel density estimator (KDE) with plug-in bandwidth selection map for the Kamloops Lake ram band; 95% isopleth covers 64.5km^2, 50% isopleth covers 9.4km^2; the smoothing parameter h=337m;

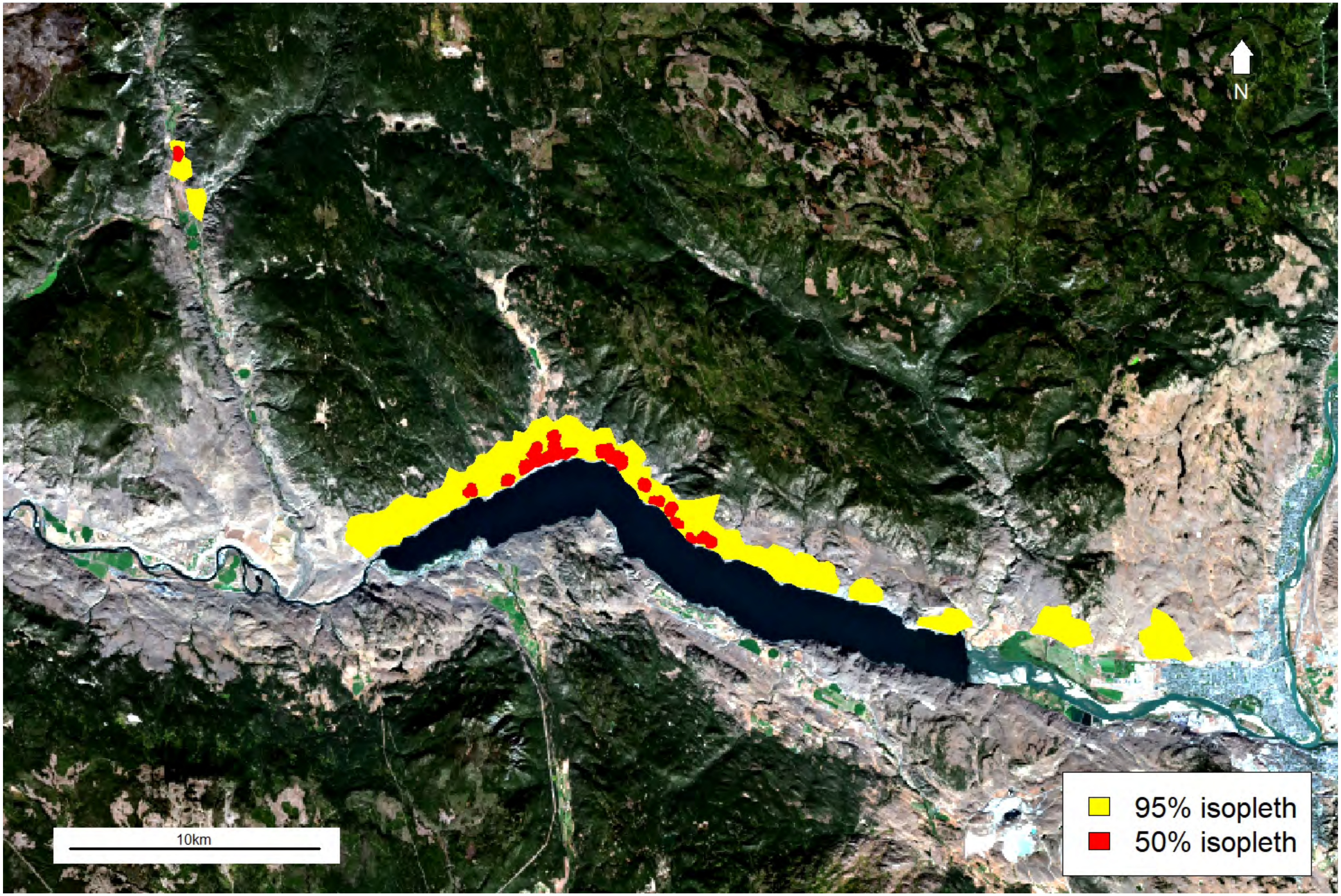

Fig.2c: Adaptive local convex hull (LoCoH) map for the Kamloops Lake ram band; 95% isopleth covers 38.5km^2, 50% isopleth covers 4.8km^2; the adaptive parameter a=46,093m;

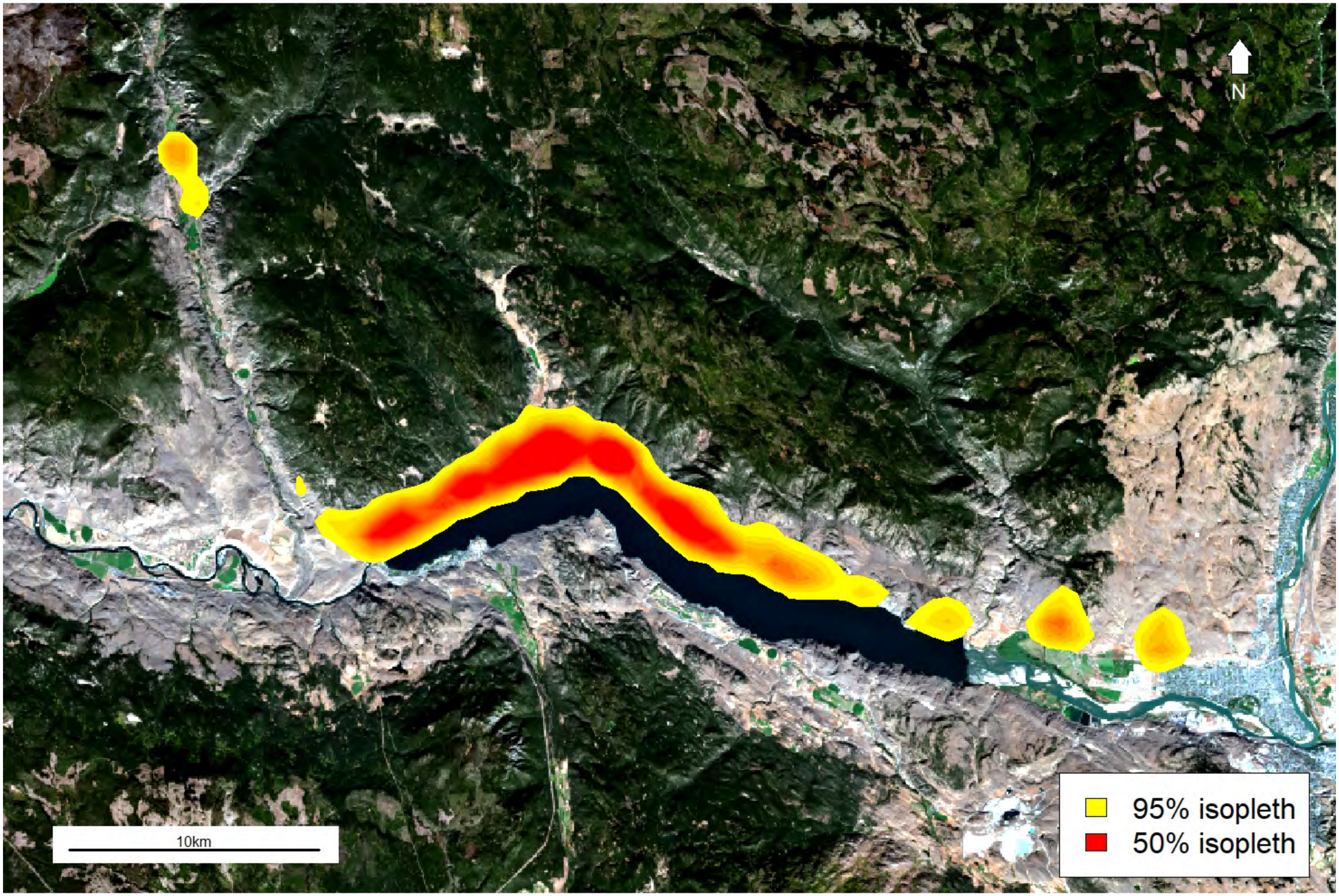

Fig.2d: Biased random bridge (BRB) map for the Kamloops Lake ram band; 95% isopleth covers 71.5km^2, 50% isopleth covers 9.7km^2; the upper recording time threshold was set to 4 hours;

Appendix 2

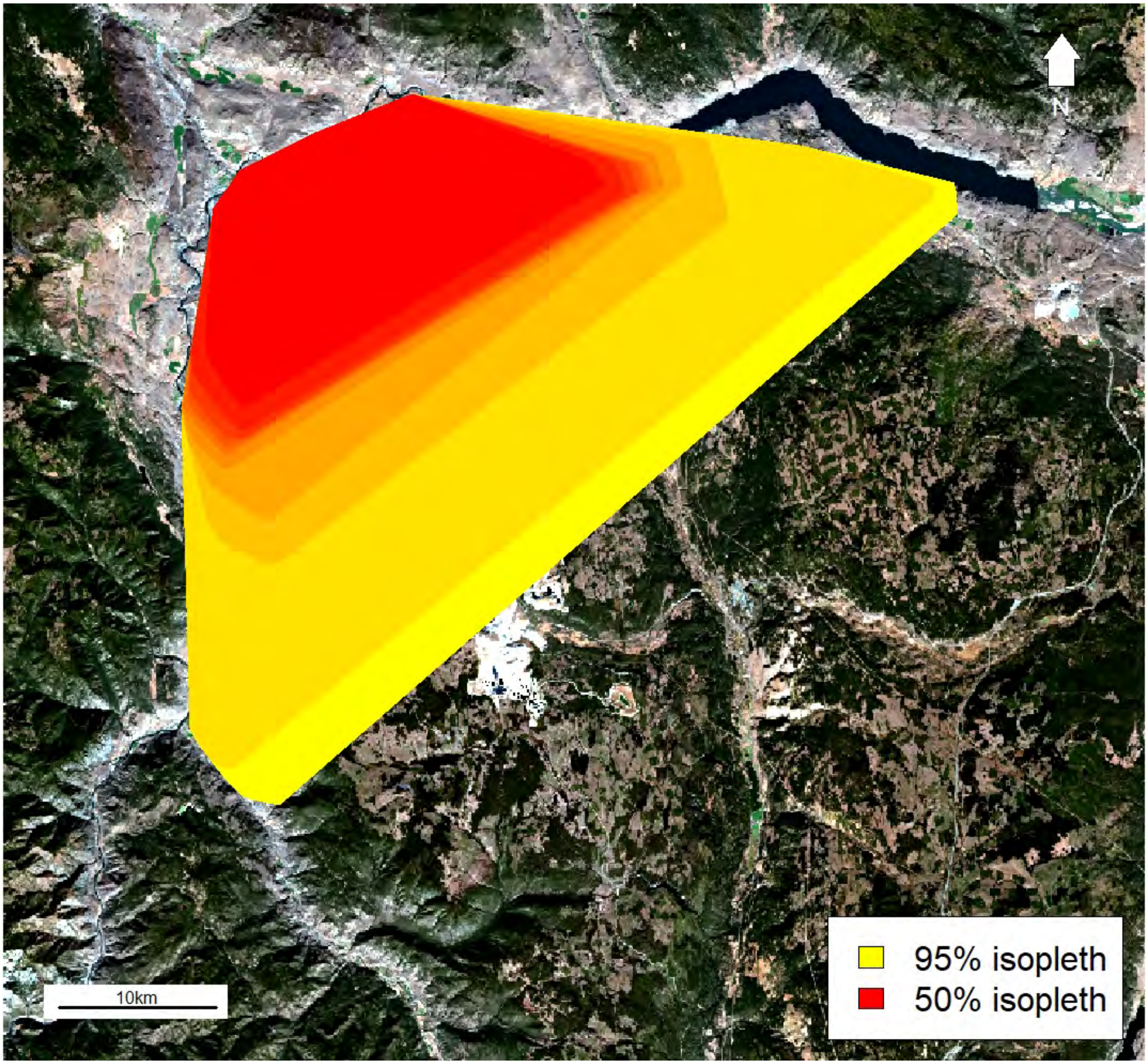

Fig.3a: Minimum Convex Polygon (MCP) map for the Spatsum ram band; 95% isopleth covers 1,344.6km^2, 50% isopleth covers 277.2km^2;

Appendix 2

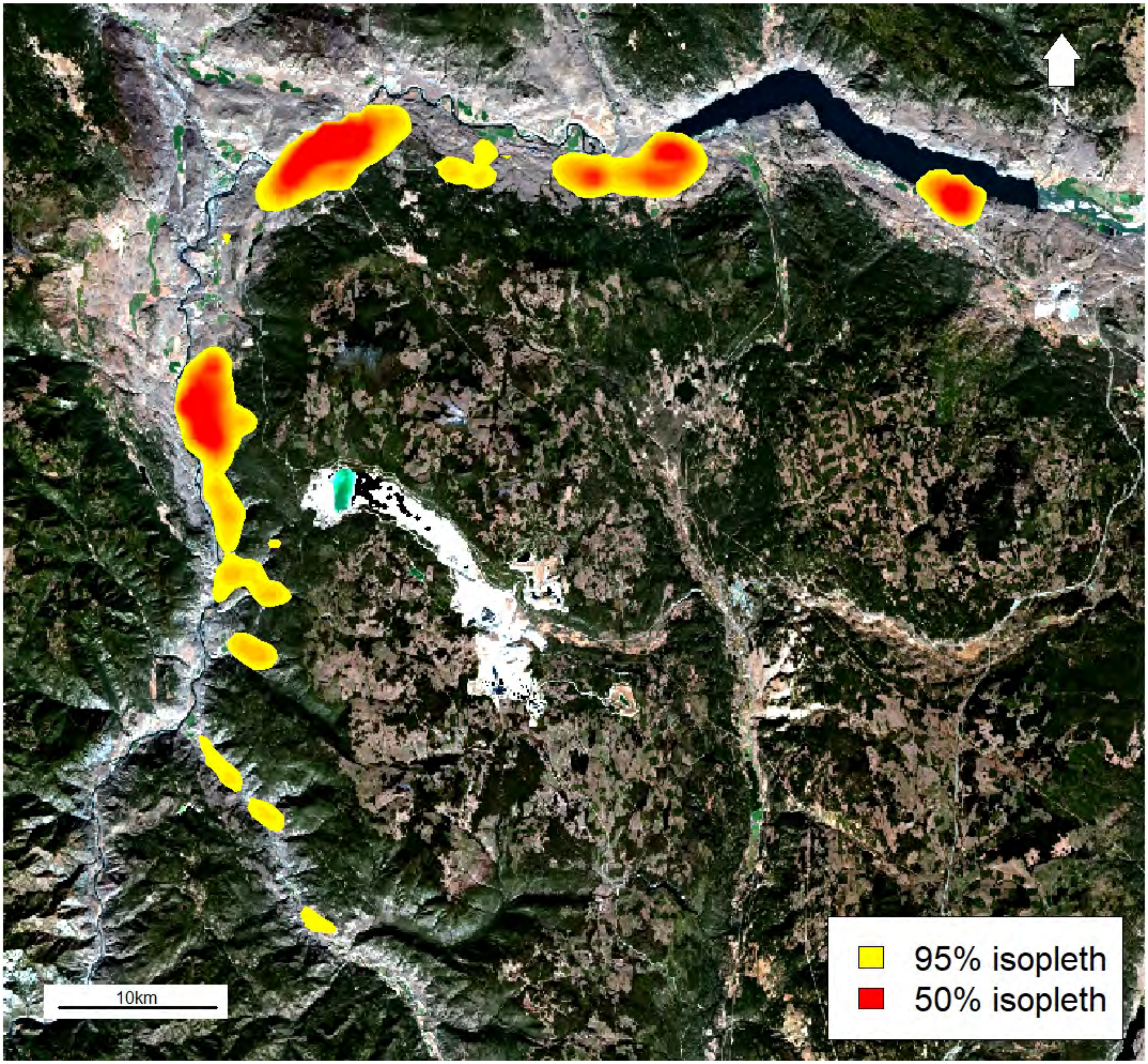

Fig.3b: Kernel density estimator (KDE) with plug-in bandwidth selection map for the Spatsum ram band; 95% isopleth covers 143.9km^2, 50% isopleth covers 19.2km^2; the smoothing parameter h=425m;

Appendix 2

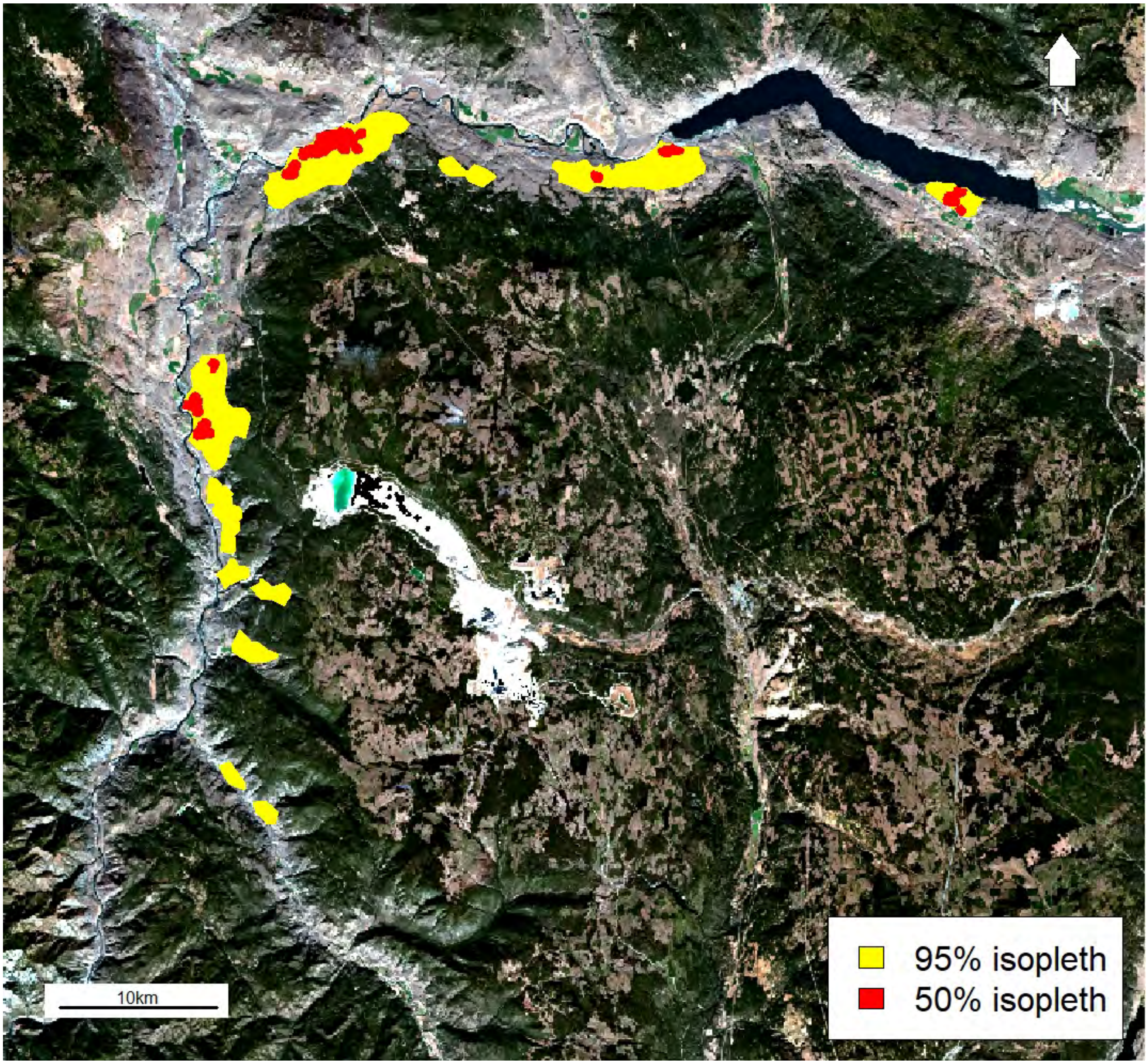

Fig.3c: Adaptive local convex hull (LoCoH) map for the Spatsum ram band; 95% isopleth covers 87.7km^2, 50% isopleth covers 12.7km^2; the adaptive parameter a=63,549m;

Appendix 2

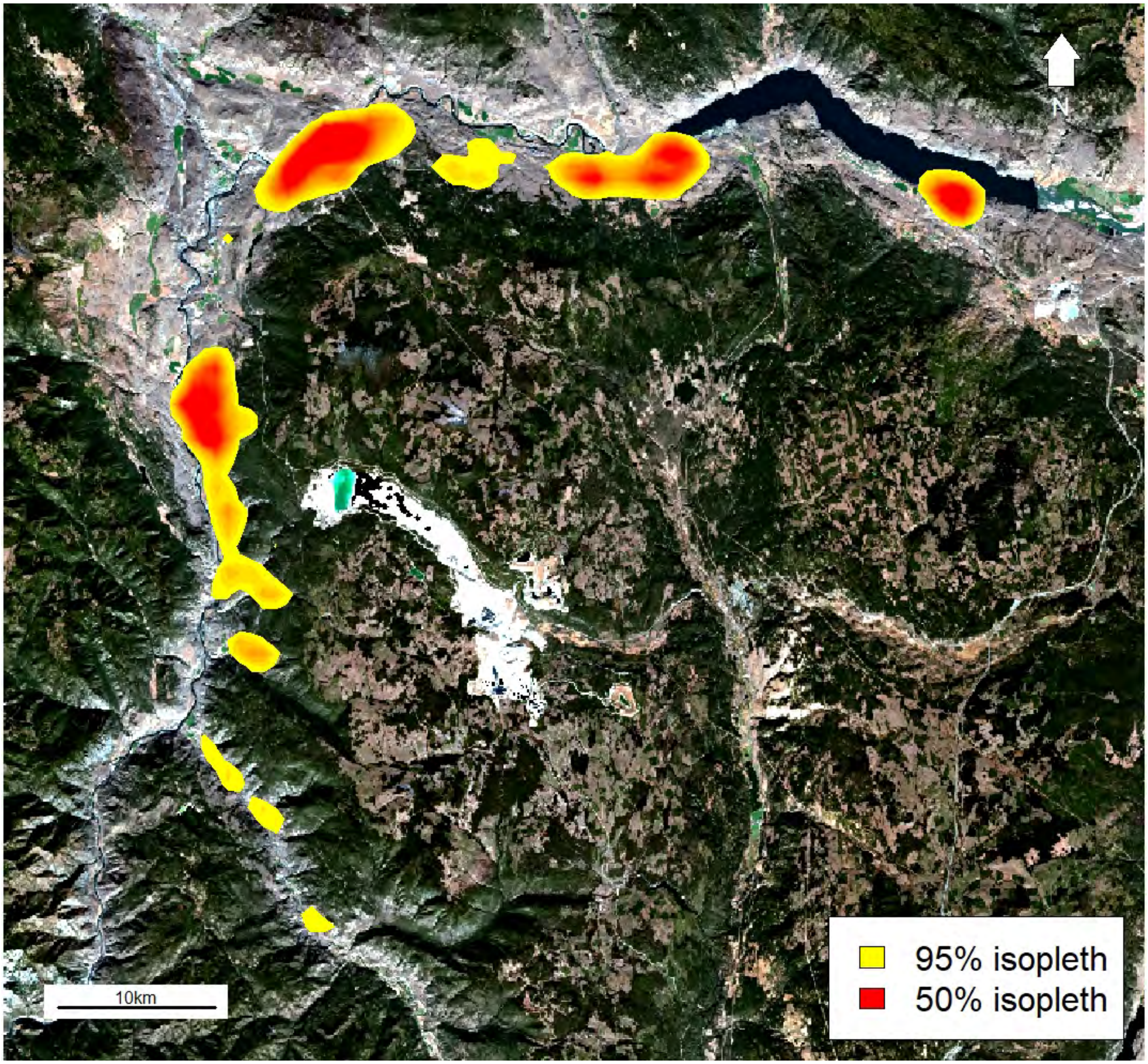

Fig.3d: Biased random bridge (BRB) map for the Spatsum ram band; 95% isopleth covers 157.5km^2, 50% isopleth covers 20.3km^2; the upper recording time threshold was set to 4 hours;

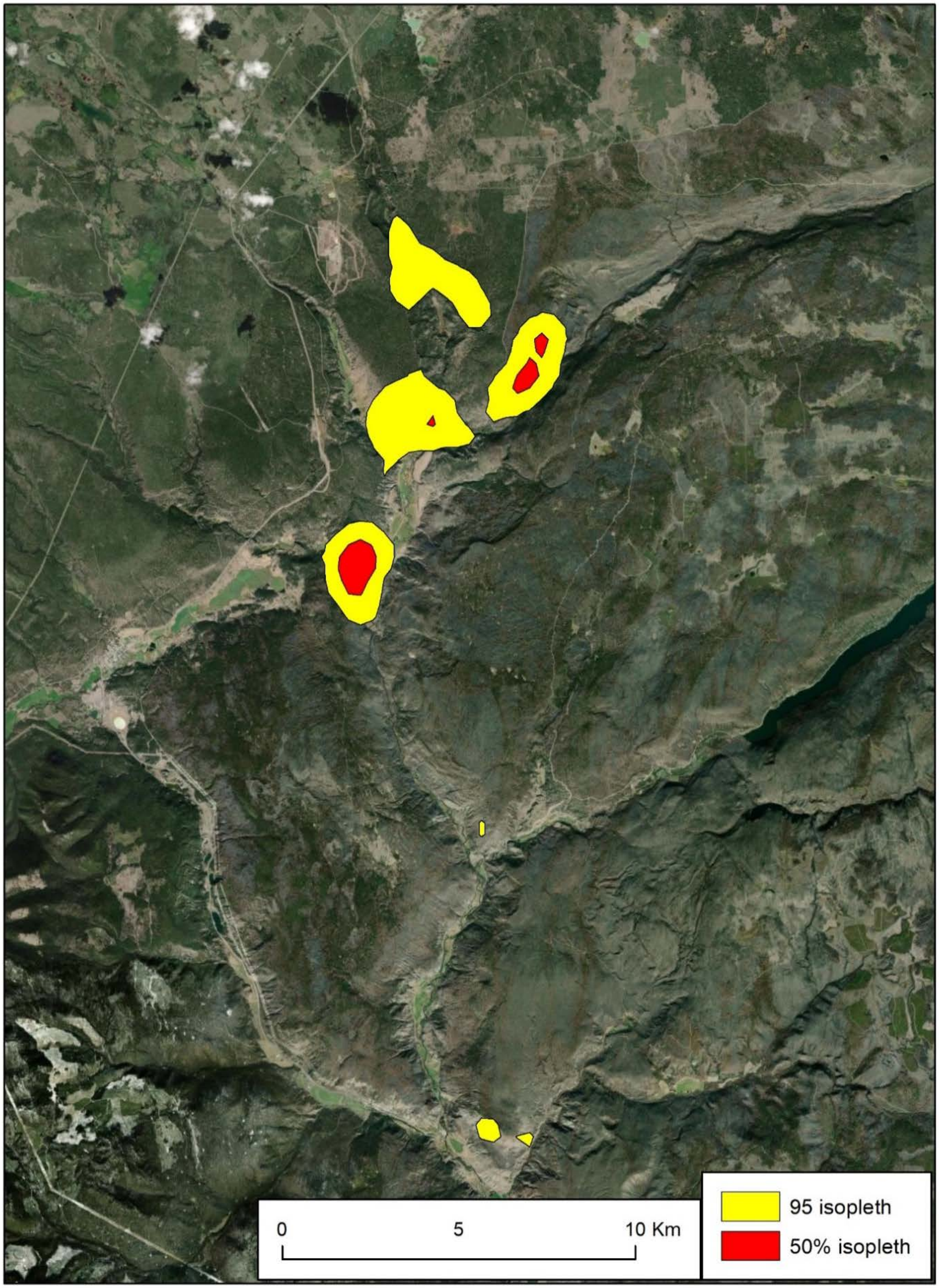

Fig.4b: Kernel density estimator (KDE) with plug-in bandwidth selection map for Chasm ram band; 95% isopleth covers 18.7km^2, 50% isopleth covers 1.9km^2; the smoothing parameter h=258m;

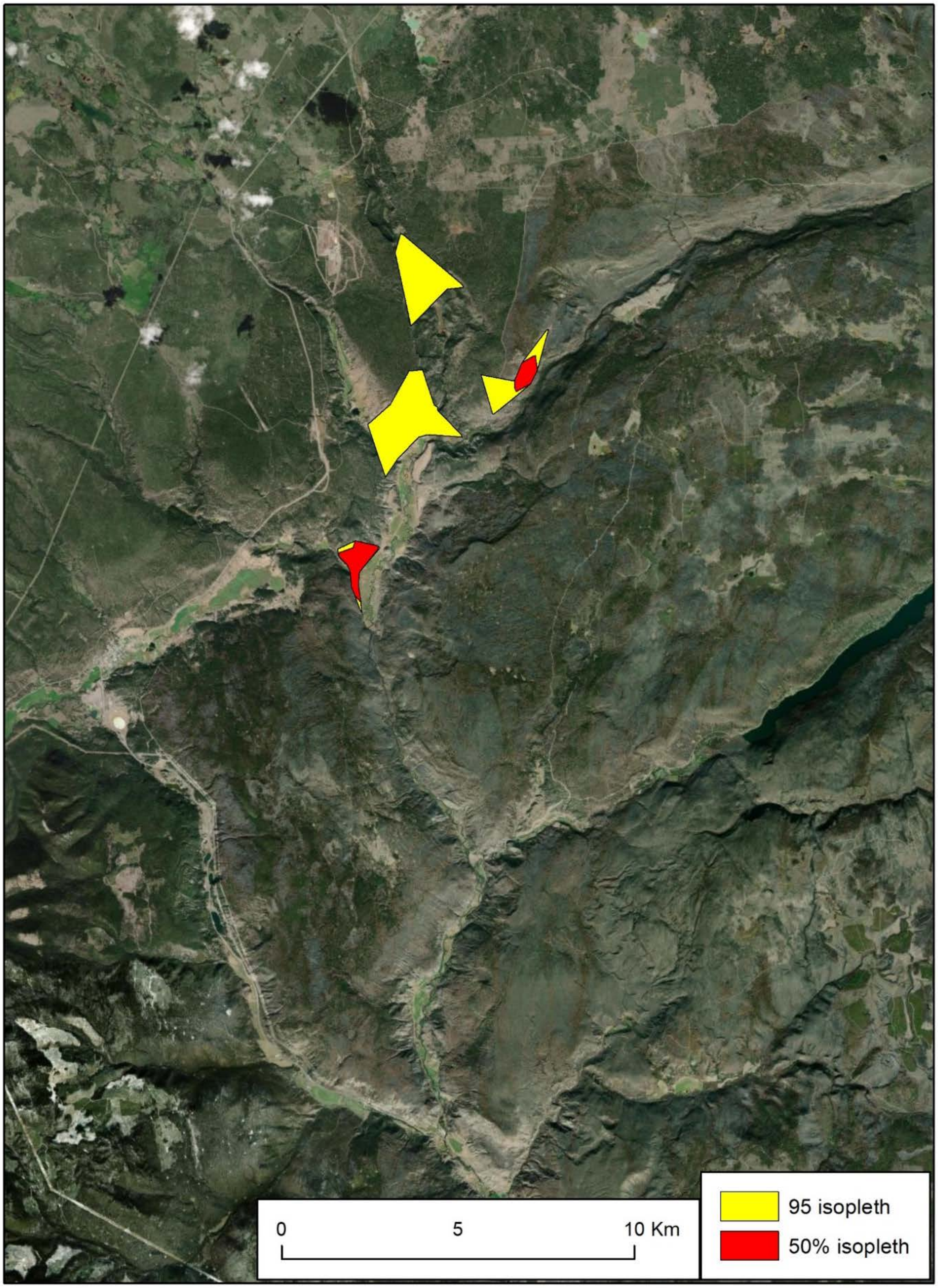

Fig.4c: Adaptive local convex hull (LoCoH) map for the Chasm ram band; 95% isopleth covers 7.3km^2, 50% isopleth covers 1.1km^2; the adaptive parameter a=34,599m;

Appendix 2

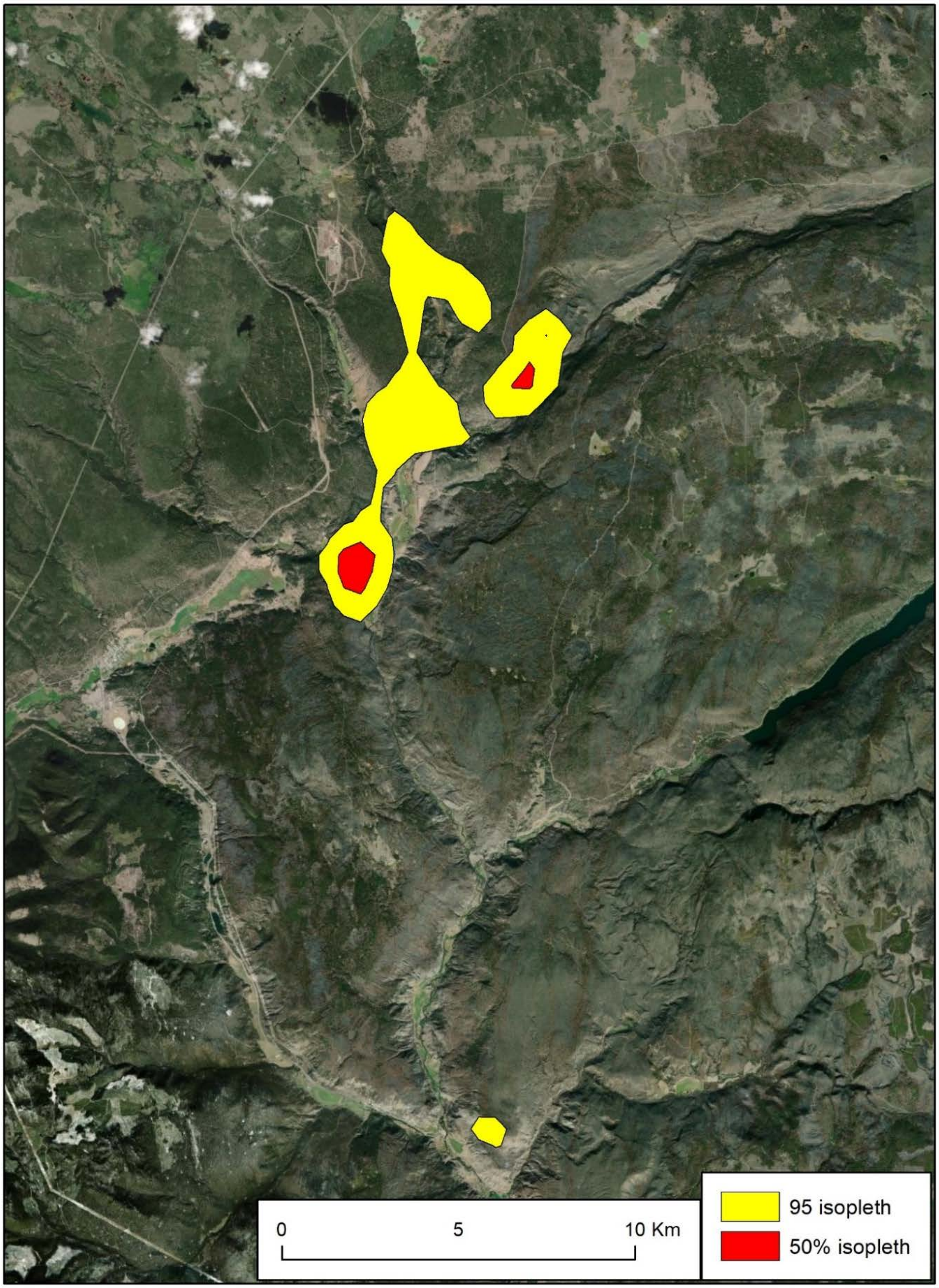

Fig.4d: Biased random bridge (BRB) map for the Chasm ram band; 95% isopleth covers 22.6km^2, 50% isopleth covers 1.4km^2; the upper recording time threshold was set to 4 hours;

APPENDIX 3

Seasonal home range (95% isopleth) and core range (50% isopleth) estimates obtained with adaptive LoCoH method, of three Bighorn sheep (*Ovis canadensis*) ram bands in Thompson Region, British Columbia, Canada. Insufficient data were available for the fourth band (Chasm).

The seasons were defined based on the literature (Demarchi et al. 2000; Poole et al. 2016) and BC FLNRORD. Winter was defined to span 1 December to 31 March (generally, winter has low movement rates and stable use of elevation). Spring and summer were defined to span 1 April to 24 August (this includes lambing, use of low elevation with greening-up vegetation, and increasing movement rates). Fall was defined as 25 August to 24 October (this period often is recognized as pre-rut and is characterized by variable use of elevation and declining movement rates). Mating season (rut) was defined as 25 October to 30 November.

The data were collected as a part of the Thompson Region Collaring Project lead by BC FLNRORD. For the time span of collected data please refer to Appendix 1Basemaps were obtained through publicly available data from Sentinel-2 satellite (European Space Agency, 2020) and represent area visited by the satellite on 12 June 2017.

The coordinates of the center of each map are:

- Battle Creek area: 50°46'09.0"N 121°03'10.5"W
- Kamloops Lake area: 50°46'03.0"N 120°41'19.4"W
- Spatsum area: 50°30'22.4"N 120°56'14.9"W

Appendix 3

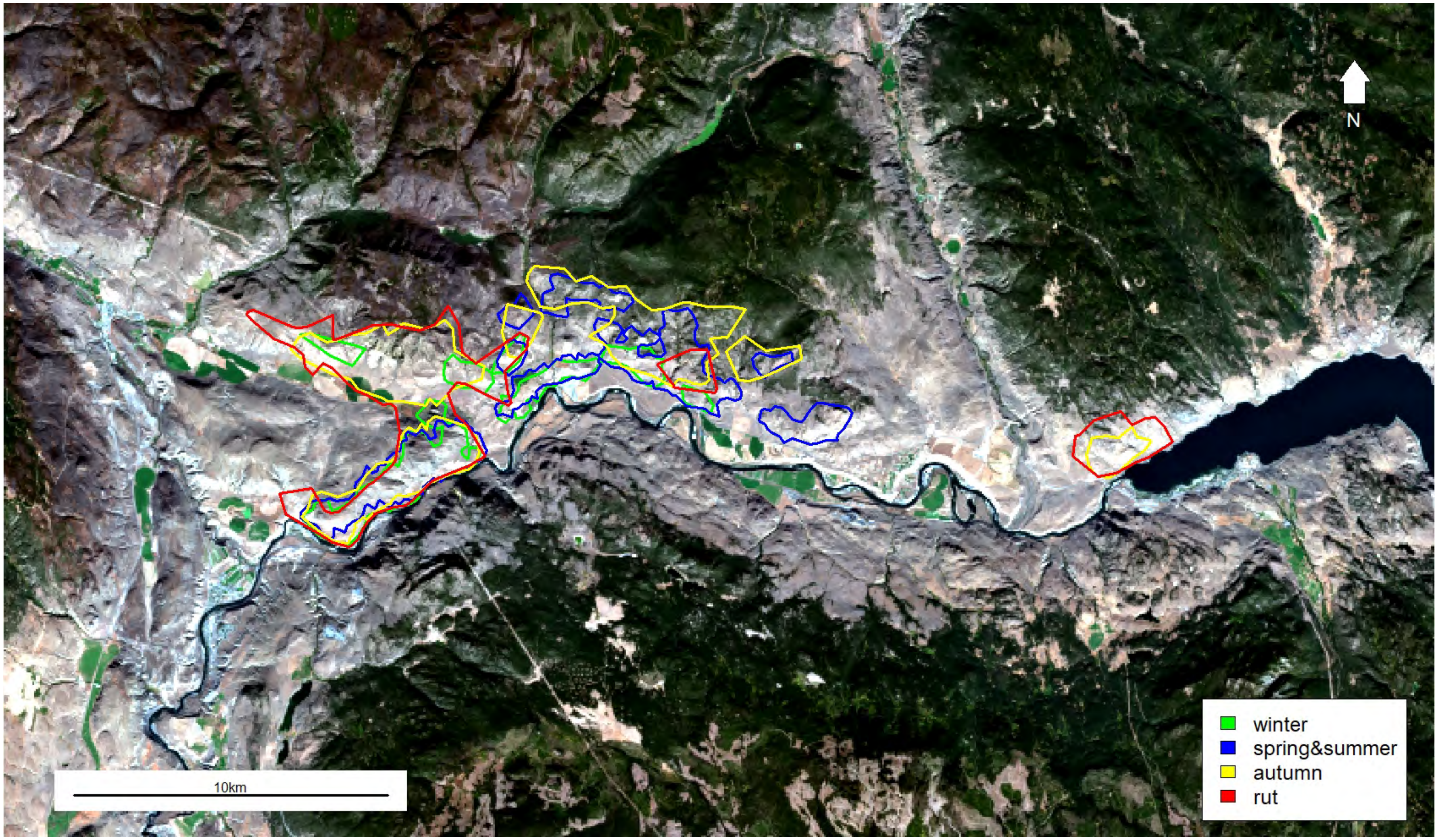

Fig.1: Visual representation of seasonal HR for the Battle Creek band; winter range covers 26.7km^2, spring and summer range covers 45.7km^2, autumn range covers 57.2km^2, and rut range covers 58.4km^2;

Appendix 3

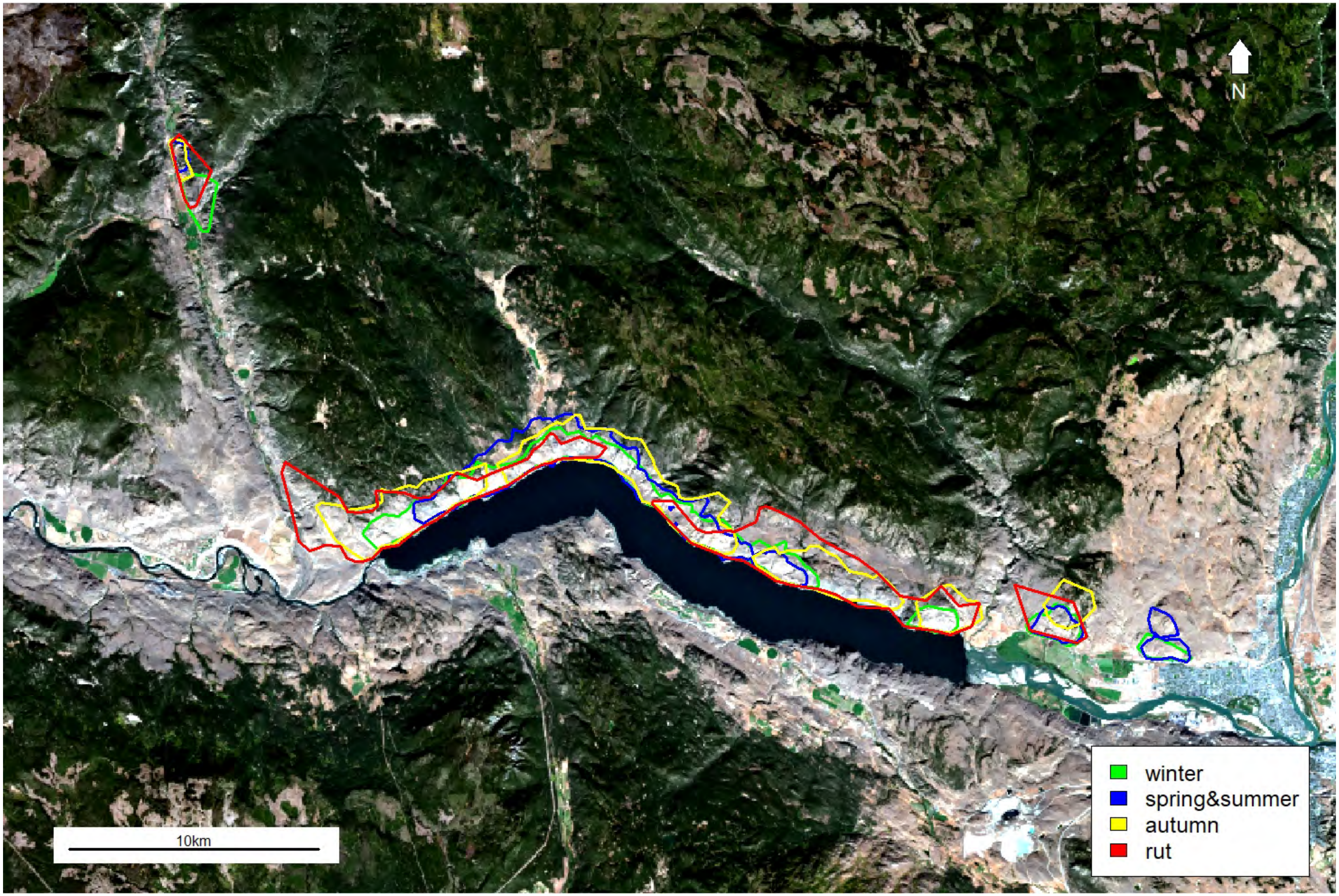

Fig.2: Visual representation of seasonal HR for the Kamloops Lake band; winter range covers 45.2km^2, spring and summer range covers 45.7km^2, autumn range covers 65.1km^2, and rut range covers 79.0km^2;

Appendix 3

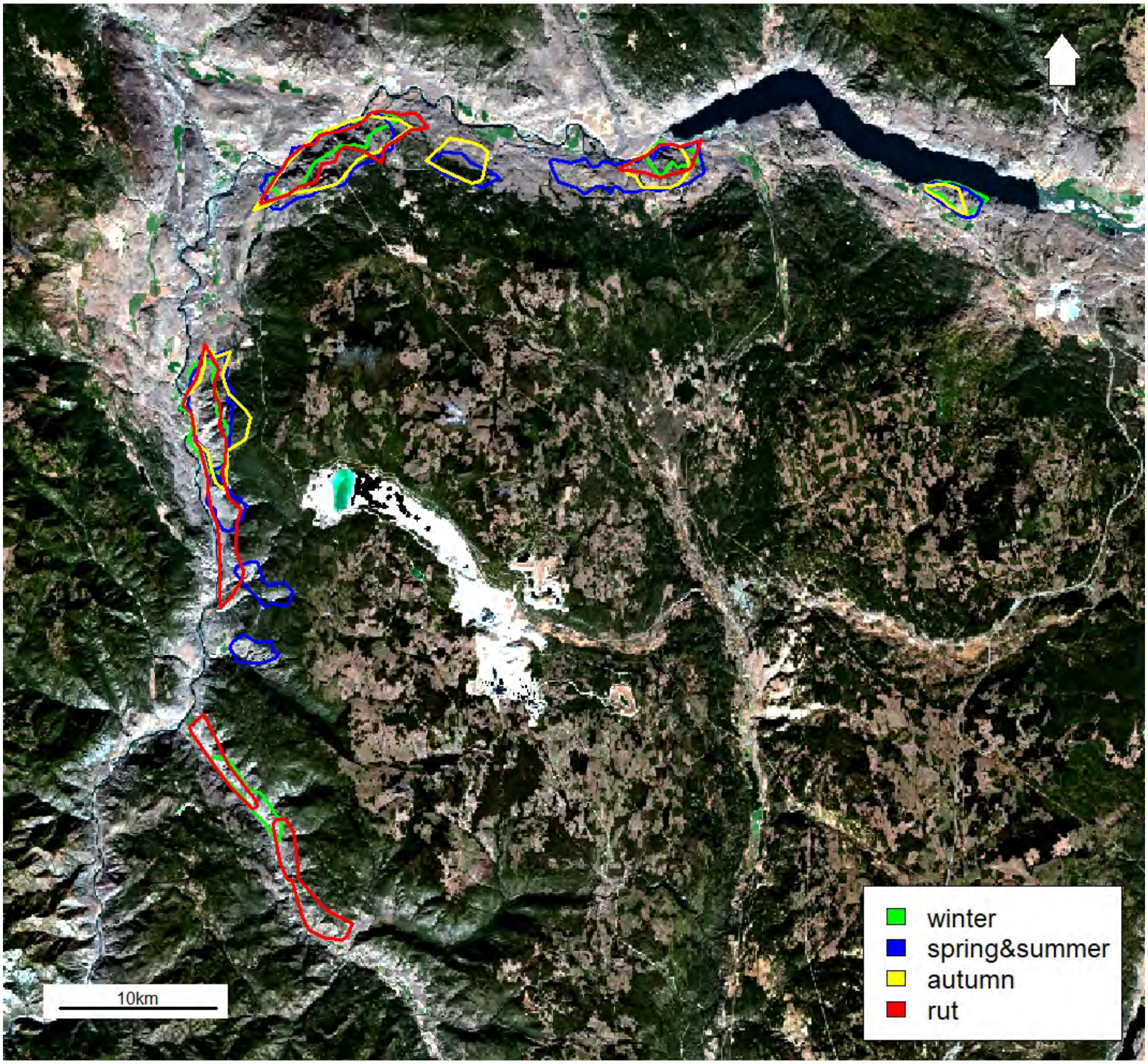

Fig.3: Visual representation of seasonal HR for the Spatsum band; winter range covers 57.3km^2, spring and summer range covers 150.9km^2, autumn range covers 81.0km^2, and rut range covers 153.1km^2;

APPENDIX 4:

Daily mean elevation change for three Bighorns sheep (*Ovis canadensis*) ram bands in Thompson Region, British Columbia, Canada. Insufficient data were available for the fourth band (Chasm).

Elevation of each location point was extracted from digital elevation model (DEM) obtained from the U.S. Geological Survey. Out of six daily location points, the mean elevation values were calculated (see Table 2.4) to develop an elevation movement profile for all rams through span of the project (2015-2018).

Four season in each year were distinguished to look for possible repetitions. See text (Chapter 2) for the working definition of the four seasons.

Appendix 4

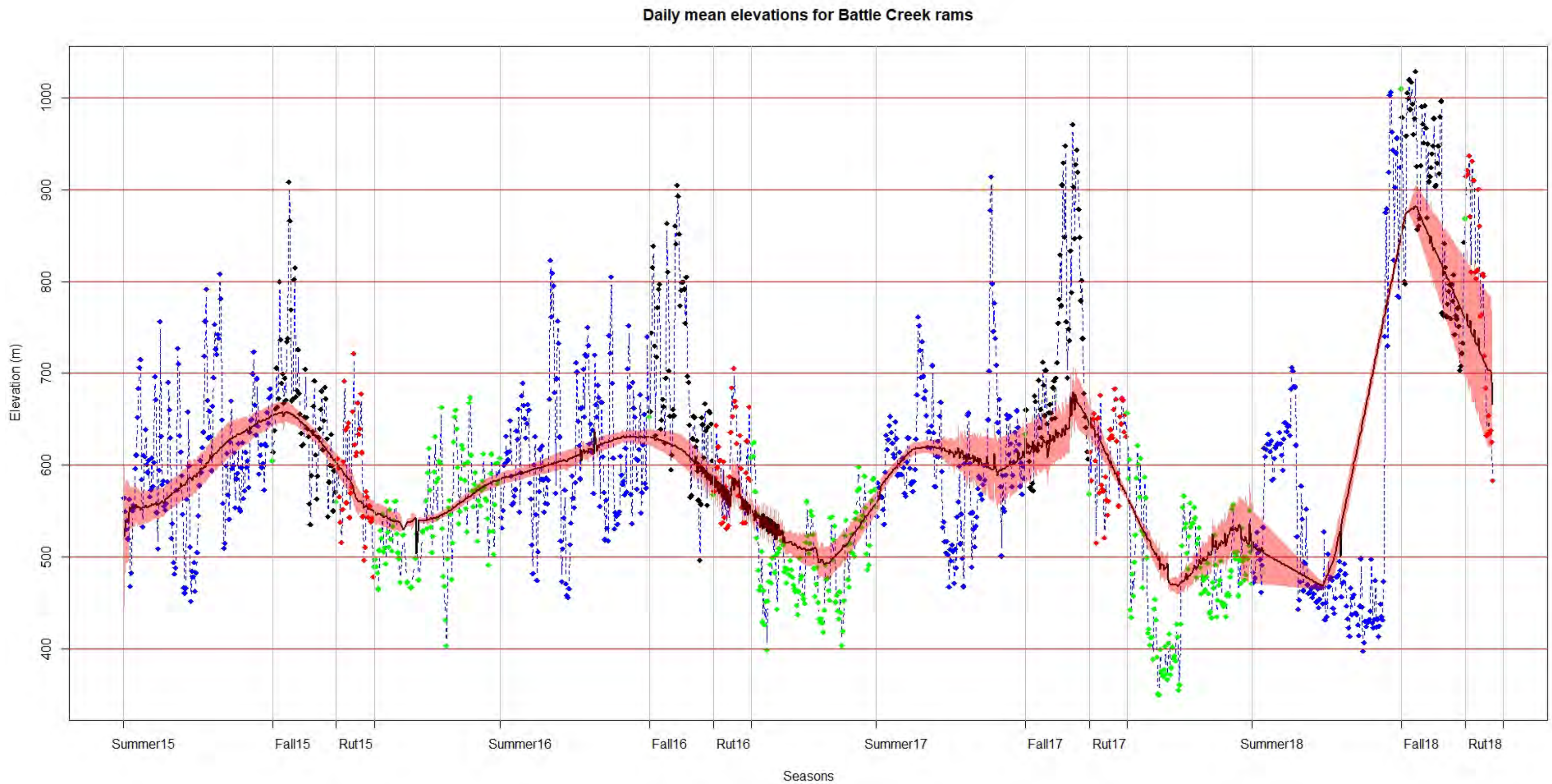

Fig. 1: Daily mean elevations for Battle Creek rams. For seasonal comparison, the same season for each year of study were distinguished by color. The black line represents smoothened elevation values (through weighted least squares method). The red polygon represents 95% confidence intervals for each point of smoothened elevation.

Appendix 4

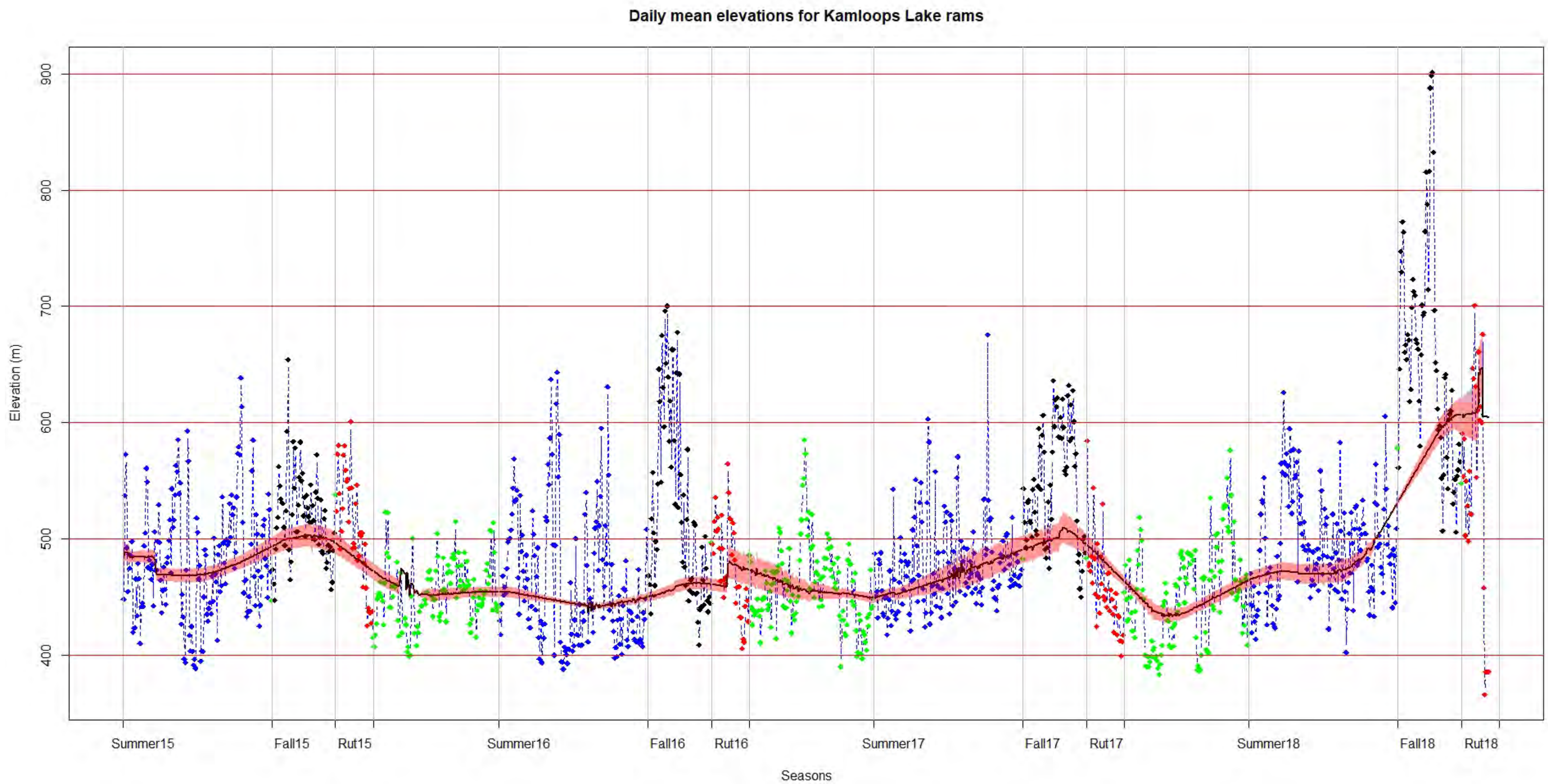

Fig. 2: Daily mean elevations for Kamloops Lake rams. For seasonal comparison, the same season for each year of study were distinguished by color. The black line represents smoothened elevation values (through weighted least squares method). The red polygon represents 95% confidence intervals for each point of smoothened elevation.

Appendix 4

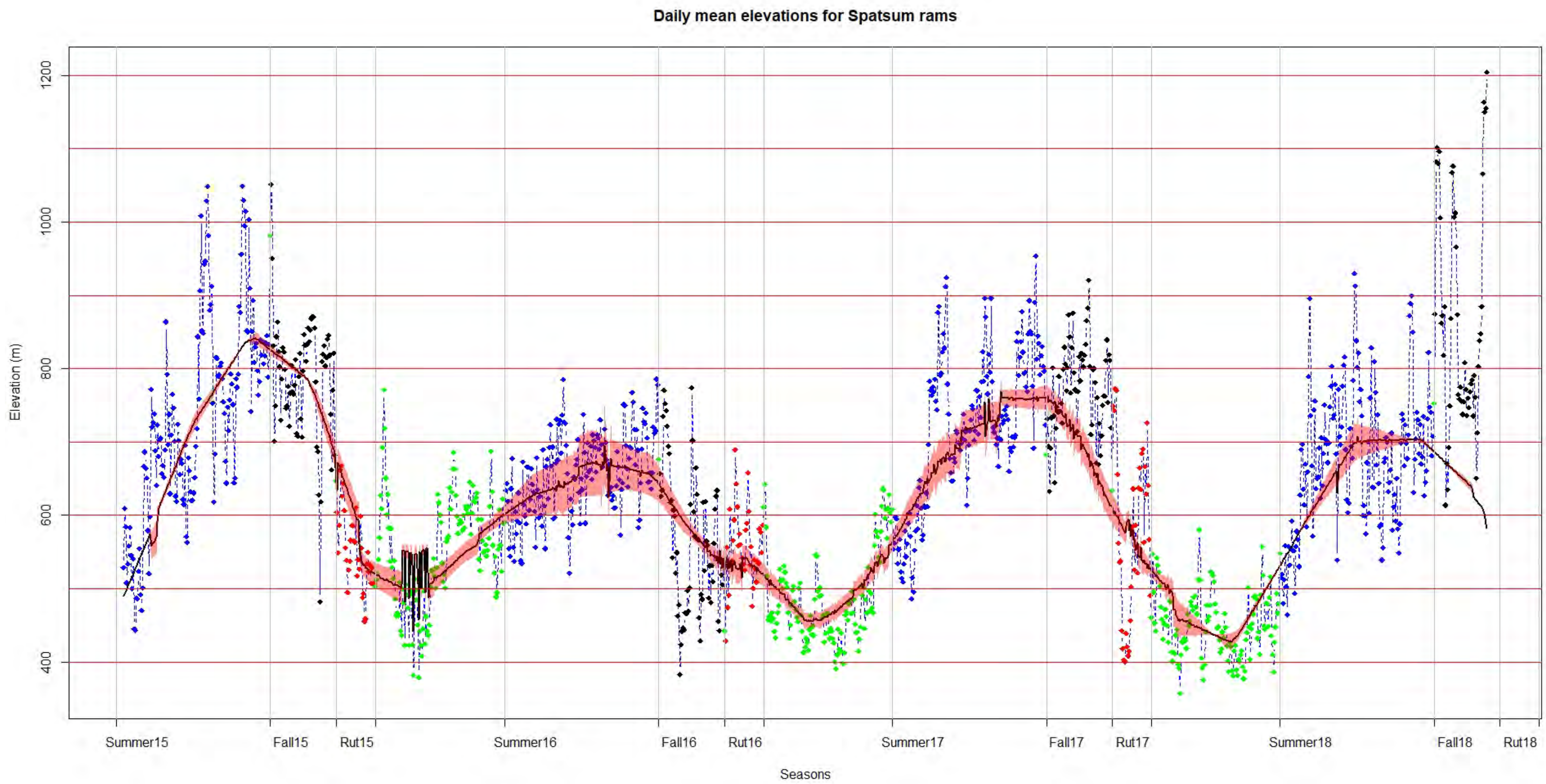

Fig. 3: Daily mean elevations for Spatsum rams. For seasonal comparison, the same season for each year of study were distinguished by color. The black line represents smoothened elevation values (through weighted least squares method). The red polygon represents 95% confidence intervals for each point of smoothened elevation.

APPENDIX 5:

Risk-of-contact as foray probabilities for three Bighorns sheep (*Ovis canadensis*) ram bands in Thompson Region within the Interior of British Columbia, Canada overlaid on source habitat layer.

Foray probability is shown as a gradient, with the highest probability near the overall HR, the probability decreases with the distance from the HR but also for the non-habitat areas.

Insufficient data were available for the fourth band (Chasm). See text (Chapter 3) for the working definition of the source habitat and risk-of-contact.

The coordinates of the center of each map are: 50°32'N 120°54'W.

The data ware collected as a part of Thompson Region Collaring Project lead by BC FLNRORD. For the time span of collected data please refer to Appendix 1.

ArcGIS ver. 10.7 was used to create those maps.

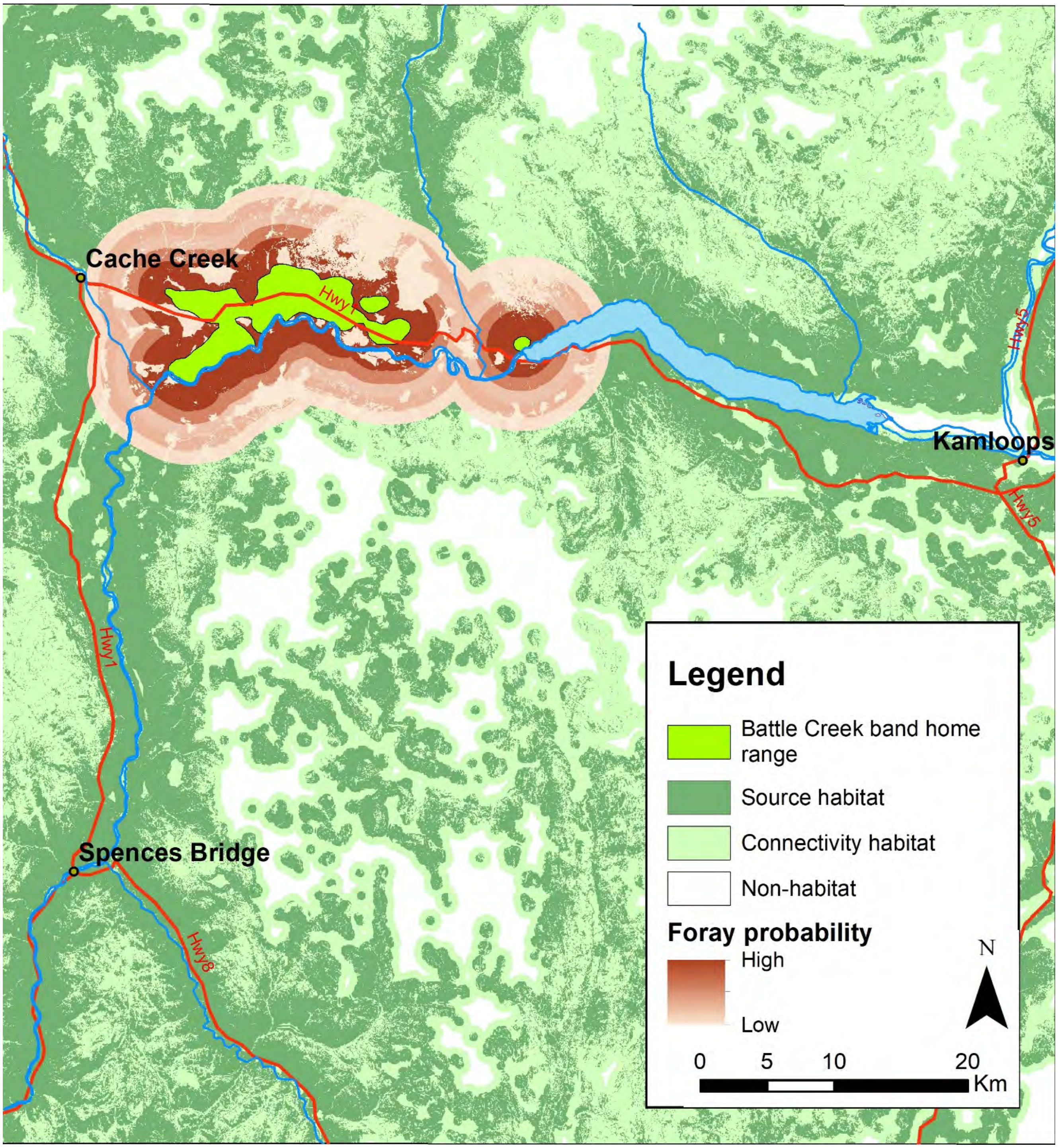

Fig. 1: Foray probability raster generated in the Risk of Contact Tool for the **Battle Creek rams** in Thompson Region within the Interior of British Columbia, Canada. No recognition of natural barriers leads to portraying probabilities for not-accessible areas.

Appendix 5

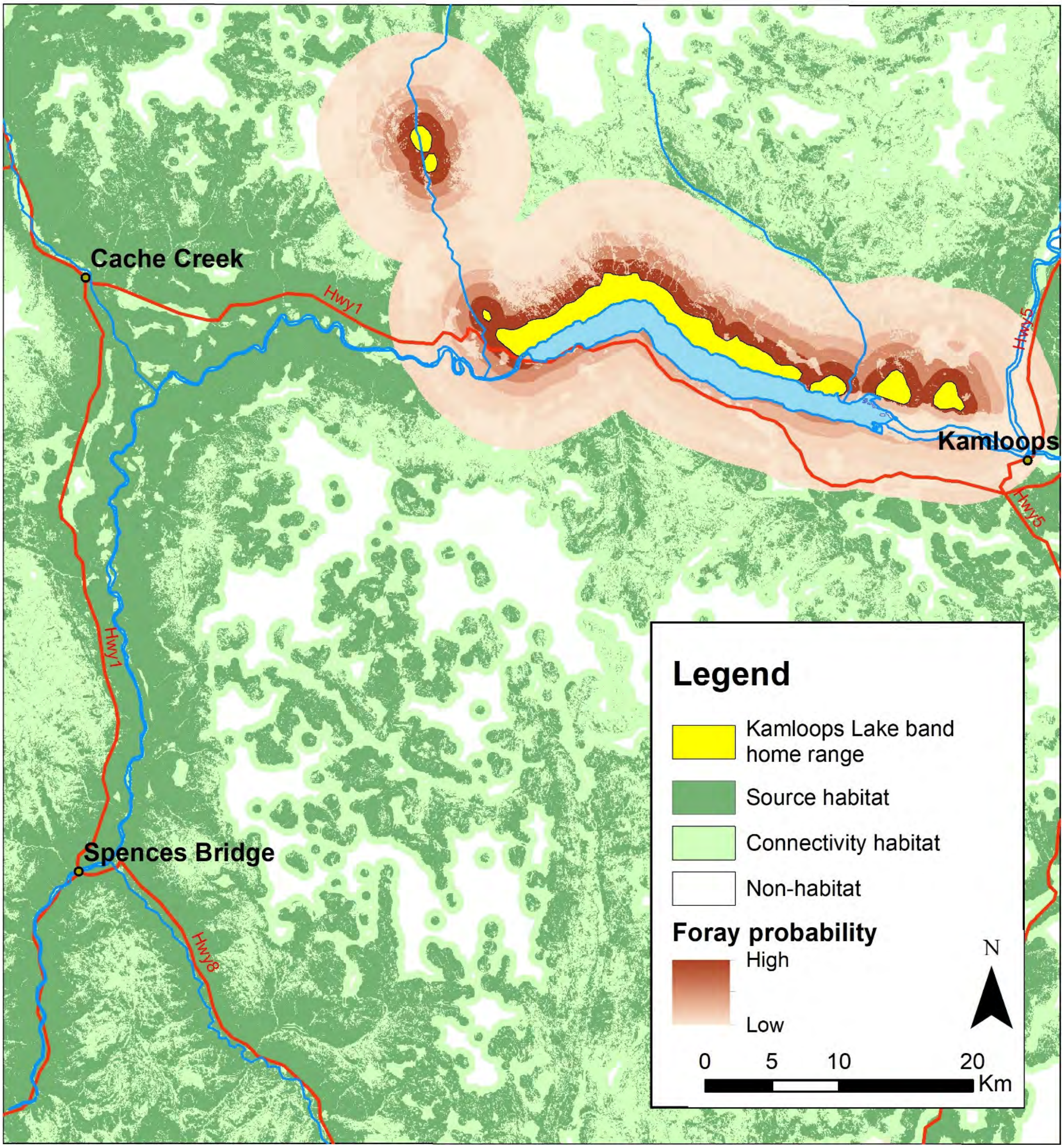

Fig. 2: Foray probability raster generated in the Risk of Contact Tool for the **Kamloops Lake rams** in Thompson Region within the Interior of British Columbia, Canada. No recognition of natural barriers leads to portraying probabilities for not-accessible areas.

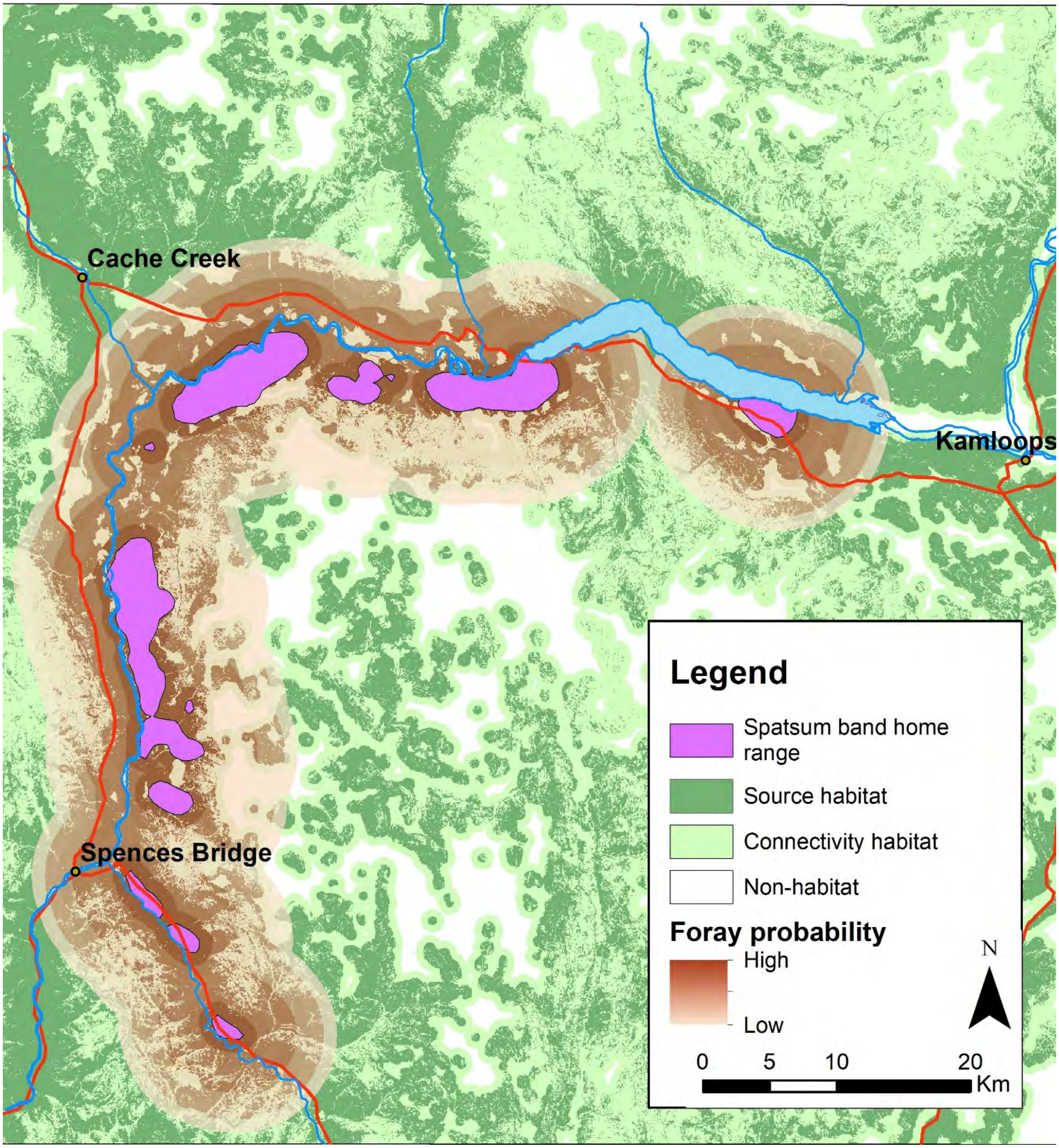

Fig. 3: Foray probability raster generated in the Risk of Contact Tool for the **Spatsum rams** in Thompson Region within the Interior of British Columbia, Canada. No recognition of natural barriers leads to portraying probabilities for not-accessible areas.