Beavers (*Castor canadensis*) in Nunavik: integrating multiple ways of knowing to address climate change concerns related to the expansion of boreal species into tundra regions

ᑭᒋᐊᑦ (*Castor canadensis*) ᓄᓇᕕᒻᒥ: ᐃᓚᐅᓂᕐᑎᓯᒍᑎᑦᓴᑦ ᐊᒥᓱᐃᑎᒍᑦ ᖃᐅᔨᒪᐅᓯᒍᓐᓇᑐᓂᒃ ᐱᓪᓗᒍ ᓯᓚᐅᑉ ᐊᓯᑦᔨᓯᒪᓂᕐᓂᖕᒐᓄᑦ ᐃᓱᒫᓗᑎᐅᕙᑦᑐᓄᑦ ᐃᓂᖕᒐᔪᑦ ᐃᕐᐸᔩᒥᓯᒪᓂᕐᓂᖕᒋᓐᓄᑦ ᐆᒪᔩᕙᑦᑐᑦ ᓇᑎᕐᓇᐅᔪᓂᒃ.

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ABSTRACT

Warming of the Arctic is leading to permafrost degradation, increased vegetation cover, earlier breakup of ice on rivers and lakes, and the arrival and northward expansion of new wildlife species. Beaver expansion into the Arctic has been attributed to shrubification and observed to impact the hydrology, permafrost, wildlife, and people of these regions. The objectives of this research were to 1) characterize changing beaver distribution and associated habitat characteristics in Nunavik, 2) document Inuit knowledge about beaver expansion and the impact on Inuit food security, and 3) identify adaptation strategies to minimize these impacts, while co-producing this knowledge through regional and local research partnerships and collaboration. A mixed methods and knowledge co-production research approach, which included Inuit knowledge interviews, helicopter survey of beaver lodges, dams, and food caches, community questionnaires, and habitat selection analysis, indicated that communities prioritized beaver management because of their concerns regarding the impact of beaver dams on Arctic char and associated impacts on food security. The earliest observations of beavers in the Ungava region of Nunavik occurred near Kangiqsualujjuaq in the late 1950s and near Kuujjuaq in the 1970s, with more recent observations confirming beaver presence much farther north near Aupaluk and Kangirsuk. A habitat selection analysis underlined the importance of dominant water body type as a predictor of beaver presence at both a landscape and local scale of analysis, with beaver sign most often observed along streams, then rivers, then small lakes and less commonly on large lakes. The findings demonstrate how species expansion can be better monitored by integrating western science and Inuit knowledge. Inuit observations can detect beaver impacts on other species, are sensitive to small changes, and can capture transient events, such as sightings of beavers unsuccessfully attempting to colonize a new habitat. Helicopter surveys cover larger areas than Inuit may be able to travel by land and provides systematic information on presence and absence at one point in time. Increased awareness of the distribution of beavers, associated habitat variables, and possible future colonization routes achieved through knowledge co-production can help Inuit policy makers mitigate and adapt to changing wildlife distributions and hydrological regimes.

RÉSUMÉ

Le réchauffement climatique a des impacts importants sur l'environnement arctique, notamment la dégradation du pergélisol, l'augmentation du couvert végétal, la fonte hâtive de la glace et l'expansion vers le nord de la répartition de certaines espèces animales. La croissance accrue des arbustes est considérée comme ayant contribué à la colonisation des écosystèmes arctiques par le castor qui, à son tour, peut avoir des impacts sur l'hydrologie, le pergélisol et la faune locale, mais aussi sur les peuples autochtones. Les objectifs de cette recherche étaient, pour les castors du Nunavik, de 1) caractériser le changement de leur répartition et de leur sélection de l'habitat, 2) documenter les connaissances Inuit sur leur expansion et leurs impacts sur la sécurité alimentaire locale et 3) identifier, en collaboration avec les communautés locales, des stratégies d'adaptation permettant de minimiser ces impacts. Une approche de recherche utilisant des méthodes mixtes et de co-production du savoir, incluant des entrevues avec des détenteurs de connaissances Inuit, des relevés faits par hélicoptère, des questionnaires remplis par les communautés, ainsi qu'une analyse de sélection de l'habitat, a indiqué que les communautés priorisent la gestion du castor en raison de leurs préoccupations sur les impacts des barrages de castor sur l'omble chevalier et des impacts qui en découlent sur la sécurité alimentaire. Les premières observations de castors dans la région de l'Ungava ont eu lieu près de Kangiqsualujjuaq à la fin des années 1950 et près de Kuujjuaq dans les années 1970. Des observations récentes confirment leur présence près d'Aupaluk et de Kangirsuk. L'analyse de la sélection de l'habitat du castor au Nunavik a démontré que le type de plan d'eau est le meilleur indicateur de leur présence, les ruisseaux étant fortement sélectionnés, suivi par les rivières et finalement par les petits lacs. Les résultats ont mis en évidence comment l'expansion des espèces dans l'arctique peut être mieux surveillée en intégrant les connaissances Inuit aux connaissances scientifiques. Les fréquentes observations des Inuit sur de longues périodes peuvent servir à détecter les impacts des castors sur d'autres espèces, et sont sensibles aux changements transitoires de moindre envergure, tels que les tentatives infructueuses de colonisation de nouveaux habitats par le castor. D'un autre côté, les relevés par hélicoptère peuvent couvrir une plus grande superficie, mais ne permettent de détecter que des modifications évidentes à un moment précis. Une meilleure connaissance de la répartition des castors, de l'habitat qu'ils sélectionnent et qu'ils pourront coloniser, peut aider les utilisateurs et les gestionnaires Inuit à s'adapter aux changements associés à l'expansion des castors et à mieux préparer des mesures d'atténuation.

ᓄᓪᓕᑎᕐᓯᒋᑦ

ᐅᕐᕈᓯᕙᓪᓕᐊᓂᖓᑦ ᐅᑭᐅᕐᑕᑐᒥ ᐊᒥᓱᐃᑎᒍᑦ ᓱᕐᕂᓂᖅᐸᓪᓕᕐᒪᑦ ᐃᓚᒋᔭᐅᑎᓪᓗᒍ ᐊᐅᔭᐃᑦᑐᑕᖏᑦ ᓄᓇᐅᑉ ᐃᑭᐊᖓᓃᑦᑐᑦ ᐊᐅᕙᓪᓕᐊᕙᓪᓕᕐᒪᑕ, ᐱᕆᕐᑐᕗᓪᓗ ᐱᕆᕐᑐᐹᓘᕙᓪᓕᕐᓯᑎᒃ, ᓯᑯᐃᑦ ᓱᐱᑦᓴᐅᑎᓲᖑᓪᓕᕐᓯᑎᓗ ᑰᓐᓂ ᑕᓯᕐᓂᓗ, ᑎᑭᑦᑕᐸᓪᓕᕐᓯᑎᒃ ᑕᕐᕿᓪᓕᐊᑯᑦᓯᒨᕐᐸᓪᓕᐊᑐᐃᓐᓇᓱᑎᓗ ᓄᑖᑦ ᐆᒪᔪᐃᑦ. ᐅᕐᐱᑖᕐᔩᒥᓯᒪᔭᐹᓘᓪᓕᕐᓂᖏᓐᓄᑦ ᓇᑎᕐᓇᑕᖏᑦ ᓄᓇᐅᑉ, ᐱᕚᑦᓴᑖᕐᑎᑎᓯᒪᔭᕇᔭᐅᓪᓕᕐᓯᓂᓗ ᑭᒋᐊᓂᒃ, ᓱᕐᕂᓂᖅᐸᓪᓕᕐᓯᑎᒃ ᑰᑦᑕᓂᐅᔭᓂᒃ, ᐊᐅᔭᐃᑦᑐᔭᕐᑯᑎᑦᑎᓂᒃ, ᐆᒪᔭᕐᑯᑎᑦᑎᓂᒃ ᐃᓄᕐᑯᑎᑦᑎᓂᓗ. ᑐᕋᒋᔭᖏᑦ ᑕᒪᑐᒪᐅᑉ ᖃᐅᔨᓴᕐᕚᖅᓂᐅᔩᑉ 1) ᑐᑭᓯᓇᕐᑎᓯᓂᖅ ᐊᓯᑦᔨᓯᒪᓪᓕᕐᓂᖏᑦᑕ ᑭᒋᐊᑦ ᐃᕐᐸᓯᒪᓪᓕᕐᓂᖏᓐᓄᑦ ᓇᓂᑯᑦᓯᐊᓃᓱᖑᒻᒪᖕᒌᑕᓗ ᓄᓇᕙᒻᒥ 2) ᐊᓪᓚᓗᒋᑦ ᐊᑐᐊᓚᑦᓴᖑᕐᑎᓗᒋᑦ ᐃᓄᐃᑦ ᖃᐅᔨᒪᐅᓯᖏᑦ ᐱᓪᓗᒋᑦ ᑭᒋᐊᑦ ᐃᕐᐸᓯᒪᓪᓕᕐᓂᖏᓐᓄᑦ ᖃᓄᕐᓗ ᑕᒪᓐᓇ ᐃᕐᐸᓯᒪᓪᓕᕐᓂᐅᔭᖅ ᓱᕐᕂᓂᖅᐸᓪᓕᕐᒪᖔᑕ ᐃᓄᐃᑦ ᓂᖅᑮᓪᓘᑌᓕᓚᓯᐊᕐᐸᓂᖏᓐᓂ, ᐊᒻᒪᓗ 3) ᓇᓗᓄᕐᔪᓗᓂ ᐸᕐᓇᓯᒪᐅᑎᓕᐊᖑᒍᓐᓇᑐᓂᒃ ᐃᑯᓪᓚᒪᑎᑦᔪᓇᓯᐊᕈᑎᐅᕈᓐᓇᓚᔭᕐᑐᓂᒃ ᑕᒪᒃᑯᓄᖓ ᓱᕐᕋᑕᐅᓂᕐᓘᓂᐅᔪᓄᑦ ᑭᒋᐊᓄᑦ, ᐱᖕᖑᐃᒍᑎᒋᑦᓴᓇᕐᒥᓗᒍ ᑕᒪᑦᓯᒥᖓ ᖃᐅᔨᒪᐅᓯᐅᓕᕐᑐᒥᒃ ᓄᓇᓕᓖᒪᑎᒍᑦ ᓄᓇᓕᓐᓃᑐᓄᓗ ᖃᐅᔨᓴᖃᑕᐅᕈᓐᓇᕋᔭᕐᑐᓄᓗ ᑲᑐᑦᔨᖃᑎᒋᒍᓐᓇᓗᒋᓗ. ᐅᐊᕈᕐᔪᒪᔪᒥᒃ ᐃᓗᓕᕐᑕᖃᕐᓗᓂ ᖃᐅᔨᓵᔨᐅᒍᓐᓇᑐᓂᒃ ᖃᐅᔨᒪᐅᓯᐅᔪᓂᓗ ᖃᐅᔨᓴᕐᓂᐅᒎᒪᕐᑐᖅ, ᐃᓚᖃᕐᓗᓂ ᐃᓄᐃᑦ ᖃᐅᔨᒪᐅᓯᖏᓐᓂᒃ ᐊᐱᕐᓯᑕᐅᑲᑦᑕᓂᕙᓂᑎᒍᑦ, ᕿᓕᒥᒎᓕᑎᒍᑦ ᖃᐅᔨᓴᕐᓂᖃᕐᓗᓂ ᑭᒋᐊᑦ ᓇᔪᒋᓕᕐᑕᖏᓐᓂ ᓯᒥᑦᑐᒪᓕᕐᑕᖏᓐᓂᒃ ᓂᕿᖃᕐᕙᒋᓲᖏᓐᓂᓗ, ᓄᓇᓖᓐᓂᒥᐅᓄᐊᖓᔭᐃᓪᓗ ᐊᐱᕐᓱᑏᑦ, ᓇᔭᒋᕙᓕᕐᑕᖏᑦᑕ ᑭᒋᐊᑦ ᕿᒥᕐᕈᓂᐅᔭᓂᒃ, ᓇᓗᓄᕐᔪᓚᕿᓯᒪᓕᕐᒪᑕ ᓄᓇᓖᑦ ᓯᕗᓪᓕᐅᔭᐅᓚᑦᓴᕐᑯᑎᖃᓕᕐᓯᑎᒃ ᑭᒋᐊᑦ ᐊᐅᓚᑕᐅᑦᓯᐊᔩᒥᒋᐊᖃᓕᕐᓂᖏᓐᓄᑦ ᓲᕐᓗ ᑲᒪᒋᔭᐅᑦᓯᐊᔩᒥᓗᑎᒃ ᐃᓱᓕᓗᒃᑲᒥᒃ ᑭᒋᐊᑦ ᓯᒥᑦᑌᕙᓐᓂᖏᑦ ᑰᓂᒃ ᓱᕐᕂᓂᕐᓗᓂᖃᓯᓗᑎᒃ ᐃᖃᓗᐸᓂᒃ ᐊᓯᖏᓐᓂᓗ ᐆᒪᔪᓂᒃ ᓲᕐᓗ ᓂᖅᑮᓪᓘᓚᓪᓚᕿᑎᑕᐅᒍᒪᖖᒋᒎᑦ. ᑭᒋᐊᑦ ᑎᑭᓕᒪᓕᒋᐊᖏᑦ ᐅᖓᕙᒍᑦ ᓄᐱᑕᐅᒋᐊᖕᖓᓚᐅᕐᑐᕚᓃᑦ ᑲᖏᕐᓱᐊᓗᑦᔭᐊᒥ 1950 ᐊᕐᕋᒍᖏᑦᑕ ᐃᓱᖏᓐᓂ ᑰᑦᔭᐊᓗ ᒥᑦᓯᖓᓂ 1970 ᐊᕐᕋᒍᖏᓐᓂ, ᖃᒻᒥᓂᑕᐅᓂᕐᓴᓗ ᓄᐱᑕᐅᕙᓪᓕᕐᓯᑎᒃ ᑕᕐᕿᑯᑦᓯᖏᓐᓂ ᐊᐅᓚᐸᓘᓪᓗ ᑲᖏᕐᓲᓗ. ᓇᔭᒋᓱᒋᓪᓕᕐᐸᖏᓐᓂ ᖃᐅᔨᓴᕐᓂᑎᒍᑦ ᓇᓗᓄᕐᔪᓂᐅᓪᓕᕐᒪᑕ ᐃᒪᕆᑦᑑᓂᑯᖓᓄᑦ ᑭᒋᐊᕐᑕᖃᓪᓕᕐᓂᖓᓄᑦ ᓄᓇᑐᐃᓐᓇᒥᐊᓪᓛᑦ ᐊᒻᒪᓗ ᓄᓇᓕᑎᒍᑦ ᖃᐅᔨᓴᕐᓯᑎᒃ, ᓱᕐᕈᐃᓯᓯᒪᓪᓕᕐᑐᑦ ᑭᒋᐊᖃᓪᓕᕐᐸᒋᐊᖏᓐᓄᑦ ᑯᓚᔫᓂᒃ , ᑰᓐᓂᒃ , ᑕᓯᐊᕈᕐᓂᒃ, ᐱᖃᓪᓗᐊᔭᖏᑦᑎᓗᒋᑦ ᑕᓯᕐᕈᑦ. ᑕᒪᒃᑯᐊ ᓄᐃᑕᐅᔭᐃᑦ ᑕᑯᑎᑦᓯᒪᑕ ᖃᓄᖅ ᑭᒋᐊᑦ ᐃᕐᐸᐸᓪᓕᐊᓪᓕᕐᓂᖏᑦ ᑲᒪᓇᓱᑦᑕᐅᓯᐊᕐᔩᒥᒍᓐᓇᕆᐊᖏᓐᓄᑦ ᑲᑐᑦᔨᕆᔭᐅᓗᑎᒃ ᖃᓪᓗᓈᑦ ᓯᑯᐃᔾᔪᓕᕆᔪᓯᖏᓐᓂ ᐃᓄᑐᐃᓐᓄᓗ ᖃᐅᔨᒪᐅᓯᖏᓐᓂᒃ. ᐃᓄᑐᐃᓅᑦ ᑐᑭᓯᒪᓕᕐᒪᑕ ᑕᑯᖃᑦᑕᓂᐅᑦᓯᑎᒃ ᑭᒋᐊᑦ ᓱᕐᕂᓂᕐᓗᓂᖃᓲᖑᒻᒪᑕ ᐊᓯᖏᓐᓂᒃ ᐅᒪᔩᔭᓂᒃ, ᓱᕐᕋᑕᐅᒍᐊᑦᑐᐊᐱᐅᓂᑯᖏᓐᓄᑦ ᐊᓯᑦᔨᓂᐊᕐᔭᐊᐱᐅᔩᓚᓗᐊᓂᒃ, ᑕᑯᖃᑦᑕᓂᐅᑦᓯᑎᓗ ᐊᕐᕈᓯᕐᕚᐅᖃᑦᑕᓂᐅᔭᓂᒃ ᑭᒋᐊᓄᑦ, ᓯᒥᑦᑐᑕᐅᒋᐊᕐᓂᐅᔭᓂᒃ ᑰᓐᓂᒃ. ᑕᒪᓐᓇ ᒪᓗᓐᓇᑎᑦᓯᒪᑦ ᓯᕗᓂᕐᒥ ᑭᒋᐊᑦ

ᐊᒥᓲᖕᖑᐸᓪᓕᐊᑐᐃᓐᓇᓛᓇᐊᖕᒋᓐᓄᑦ ᐃᑉᐱᒋᔭᐅᑦᓯᐊᖕᒋᒃᑯᑎᒃ. ᖁᓕᒥᒨᓕᑎᒍᑦ ᖃᐅᔨᕐᑕᐅᓃᑦ, ᐊᖕᒋᔪᒥᒃ ᓄᓇᒥᒃ ᖃᐅᔨᓴᑦᓯᐊᕈᑎᓯᐊᕈᓂᖅᓴᐅᖃᔭᕐᑐᖅ ᓴᓂᐊᓂ ᐃᓄᐃᑦ ᐱᓱᓪᓗᑎᒃ ᖃᐅᔨᓴᕐᓂᐊᑐᐊᕐᐸᑕ, ᐊᓯᖕᒋᓐᓂᓗ ᑕᑯᓐᓇᓚᕿᑎᑦᓯᓗᓂ ᐊᓯᑦᔨᑐᕐᑕᐅᓂᐅᓕᕐᑐᓂᒃ ᓴᕿᑕᐅᔪᐃᑦ ᐅᓪᓗᒥᒧᑦ ᑕᑯᑎᑦᓯᓚᕿᐅᑎᐅᒻᒪᑕ ᓄᓇᖃᕐᖃᓯᒪᔪᔦᑦ ᓱᑯᐃᔦᔩᓪᓗ ᖃᐅᔨᒪᐅᓯᖕᒋᑦ ᑲᑐᑦᔨᖃᑎᒌᑦᓯᐊᓕᑐᐊᕐᒪᑕ ᓱᓇᒥᓐᓂᓴᒥᒃ ᓴᕿᑰᖃᑎᒌᓲᒻᒪᑕ ᑐᑭᓯᒪᖃᑎᒌᑦᓯᐊᔩᒥᓚᕿᑦᓱᓂᓗ ᖃᓄᖅ ᑭᒋᐊᑦ ᓇᑎᕐᓇᒦᓲᖕᖑᒻᒪᖕᖔᑕ. ᑕᒪᓐᓇ ᖃᐅᔨᒪᐅᓯᖅ ᐱᖕᖑᑎᑕᐅᓚᕿᓂᐅᒻᒪᑕ ᑲᑐᑦᔨᖃᑎᖃᕐᓱᑎᒃ ᓄᓇᓕᓐᓂ ᐃᑲᔪᕐᓯᒍᒪᒧᑦ ᑐᕌᓐᓇᑐᕐᑎᒍᑦ ᑐᓴᐅᒪᓂᐊᕐᒪᑕᓗ ᓄᓇᓕᓐᓂ ᐊᐅᓚᑦᓯᒍᓯᐅᕈᓐᓇᑐᓂᒃ ᐸᕐᓇᓯᒪᐅᑎᓕᐊᖑᒪᒍᓐᓇᑐᓂᓗ. ᖃᐅᔨᒪᓂᖅᑲᕐᔩᒥᓂᒃ ᓇᓃᒻᒪᖕᖔᑕ ᑭᒋᐊᑦ ᓲᕗᓂᕐᒥᓗ ᓇᒨᖕᖔᔭᕐᑑᔭᕐᒪᖕᖔᑦ ᐃᑲᔪᕐᓯᓂᖃᕈᓐᓇᒪᑦ ᐃᓄᐃᑦ ᒪᓕᒐᓕᐅᕐᑎᖕᒋᓐᓂᒃ ᓱᖕᒋᐅᓯᓴᒐᓱᐊᓕᕐᐸᑕ ᐊᕙᑎᑦᑕ ᐊᓯᑦᔨᐸᓪᓕᐊᓂᖕᒐᓄᑦ ᐅᐸᓗᖕᖏᔭᕐᓯᒪᒍᑎᓕᐅᓕᕐᐸᑕᓗ ᑎᑭᑦᑕᐸᓐᓂᐊᑐᓂᒃ ᐆᒪᔦᓂᑦ ᐊᓯᑦᔨᐸᓕᐊᓂᖕᒋᑦᑕᓗ ᐃᒪᐅᑉ ᐊᐅᓚᒍᓯᖕᒋᑦ.

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These past three years of my thesis have been an eye-opening journey that would not have been possible without an incredible team of mentors, collaborators, and friends (and many of you are all three). I began my thesis unexpectedly in September 2018 with very minimal knowledge of Nunavimmiut (Nunavik Inuit) culture, geography, or self-determination efforts, despite living in the same province. Although I had planned to take a year to work before pursuing a graduate degree, Manuelle Landry-Cuerrier and Murray Humphries invited me to consider joining the Northern Wildlife Ecology Lab team working on Indigenous-partnered research. That decision was life-altering, and I have to say a huge thank you to Murray and Manu both for seeing potential in me and encouraging me to take that leap.

The next weeks were a whirlwind of online courses and readings to learn about Nunavik and Nunavimmiut realities as I prepared to embark on an internship with Makivik Corporation. Nothing was able to prepare me fully, but thankfully the Makivik staff welcomed me with open arms and took the time to help me along; I am so grateful to all of you for your mentorship, ideas, and advice from those early months until today. Thank you also to Nunavik Rotors (Peter Duncan) and Lukasi Whiteley Tukkiapik for your amazing work during the helicopter survey in 2019, for your keen eyes searching for beavers and for introducing me to the area. And to James May, thank you for providing opportunities to learn from your leadership and contribute in practical ways to Inuit self-determination efforts in wildlife management.

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Academically, I could have never finished this thesis without the guidance and mentorship of Northern Wildlife Ecology Lab members, especially the direction from Murray and Manuelle and the R help from Emily Stuff and Xavier Giroux-Bougard, as well as my co-supervisor, Raja Sengupta. Recognition also goes to Kirsten Bowser for her valued contribution to the creation of the Sankey plots in Chapter 1. To my statistics tutor, Harrison Goldspiel, who helped me organize my ideas and sort through possible analysis approaches, thank you for your clear explanations and encouragement. I want to also express my deep gratitude to Stephanie Chan, who came to Tasiujaq to help direct my fieldwork in 2019; thank you for being willing to be thrown into a totally unfamiliar situation with such enthusiasm and commitment.

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CONTRIBUTION OF AUTHORS

This thesis was written in the manuscript-based thesis style and consists of two manuscripts that are intended for publication. As the lead author on both manuscripts and as a Master's candidate, I met with Nunavik communities and partner organizations to discuss research priorities, outlined the research questions based on their recommendations, planned research design and fieldwork approaches, conducted or supervised the conduct of fieldwork, cleaned and analyzed the data, interpreted the results, and communicated these results to Nunavik partners.

Chapter 1, "Inuit knowledge and aerial survey observations of the distribution and impact of beavers in Nunavik", was co-authored by the Tasiujaq Nanuapiit Board and Murray M. Humphries. The Tasiujaq Nanuapiit Board is an organization, not a single person, but co-authored the manuscript together, since they contributed as a group to many parts of the research process. Members, including Billy Dan May, Willie Cain Jr., James May, Jusipi Kauki, and Johnny Cain, as well as their manager, Elena Berthe, contributed to the original idea, outlining the issue of beaver presence as a priority for the community of Tasiujaq, recommended community knowledge holders to interview, changed the direction of the research methods by removing the segment on beaver-Arctic char interactions, approved research methods proposed, accompanied and made recommendations during fieldwork, reviewed and edited questionnaires, initiated a follow-up helicopter survey in 2020, contributed to interpretation and recommendations for management, and provided feedback on presentation of results.

In both chapters, Murray M. Humphries provided direction and feedback in the development of research question, research design, analytical approaches, and figure creation. Both Murray M. Humphries and Raja Sengupta provided academic supervision, input on interpretation, and editorial direction.

GENERAL INTRODUCTION

Increasing temperatures in the Arctic due to climate change have had a multiplicity of effects on the tundra, including the thawing of permafrost, increasing vegetation cover, and earlier breakup of ice on rivers and lakes (Brubaker, Berner, Chavan, et al., 2011; Hassol, 2004; Meredith et al., 2019). These changes are transforming the Arctic ecosystem and facilitating the northward expansion of southern species (Furgal & Seguin, 2006; Meredith et al., 2019; Parmesan & Yohe, 2003; Tape, Christie, et al., 2016; Tape, Gustine, et al., 2016). Among the new species dotting the Arctic landscape is the North American beaver (*Castor canadensis*), an ecosystem engineer that modifies its surroundings mainly through the construction of dams and creation of wetlands (Brubaker, Bell, et al., 2011; Brubaker, Berner, Bell, et al., 2011; Furgal et al., 2002; Jarema, 2006; B. M. Jones et al., 2020; Jung et al., 2017; Tape et al., 2018).

Nunavik is the Inuit region in northern Quebec negotiated by the James Bay and Northern Quebec Agreement (Gouvernement du Québec, 1998) and is home to approximately 11,800 Inuit according to the 2016 census (Statistics Canada, 2016). Nunavimmiut (Nunavik Inuit) raised concerns regarding the impact of climate change on Arctic char (*Salvelinus alpinus*), which were brought to the Nunavik Climate Change Committee on Adaptation (including representatives from the Kativik Regional Government [KRG], Makivik Corporation, the Nunavik Hunting Fishing and Trapping Association [NHFTA, also known as Anguvigaq], le Ministère de l'Environnement et de la Lutte contre les changements climatiques [MELCC], and Ouranos). In the fall of 2018, I did an internship supervised by Makivik Corporation and in collaboration with the NHFTA during which I met with harvesters to synthesize community concerns and recommendations regarding Arctic char populations in Nunavik. Beaver geographic expansion in Nunavik and impacts on Arctic char emerged as a local knowledge priority during these interviews (Neelin, 2021), and this became the basis for this thesis. Tasiujarmiut (Inuit of the village of Tasiujaq) were particularly concerned about beaver impacts and the Tasiujaq HFTA (the Nanuapiit Wildlife Board) already had beaver management projects in mind, so they were the main collaborators during the research.

The main objectives of this thesis were to 1) characterize the change in beaver distribution and associated habitat characteristics in Nunavik, 2) document Inuit knowledge about beaver expansion and the impact on Inuit food security, and 3) identify adaptation strategies to minimize these impacts, while co-producing this knowledge through regional and local research partnerships and collaboration. The Literature Review provides an accessible yet comprehensive review of the extent of beaver impacts below and above the treeline on water bodies and permafrost, fish species, biodiversity, and people. This was written in response to the queries that I received from management bodies in Nunavik when they were confronted with conflicting messages about beavers and their potential positive or negative impacts on ecosystems, and was meant to introduce readers to background knowledge on beaver natural history, the role of these ecosystem engineers in the climate change narrative, the interpretation of their impacts in an Arctic context, and the possible implications of their range expansion for Inuit. Chapter 1 addresses all three objectives and was intended to incorporate diverse methods (interviews, a survey, and a questionnaire), perspectives (representing a diversity of voices), and knowledge systems (Inuit Knowledge and science) to achieve a more holistic understanding of beaver populations in the Arctic. Chapter 2 further explores objective 1 by characterizing the habitat variables conducive to beaver occupation in order to better inform adaptation strategies in objective 3. The literature review, chapter 1, and chapter 2 are all framed to respond to specific questions raised by Nunavik organizations and harvesters and to set a foundation for future community-partnered research. I lived in Tasiujaq and worked for the NHFTA during part of my thesis, which facilitated co-production of knowledge and made it possible to work with the community in person despite the challenges of COVID-19 restrictions. This simplified interactions and allowed me to keep community priorities in focus, support the formation of a beaver working group, and communicate research activities through illustrative pamphlets, radio announcements, school lessons, and research updates during meetings (while respecting the recommendations of the Nunavik Regional Board of Health and Social Services). These relationships were pivotal for the realization of this work and for the new research initiatives that have developed from the collaboration.

LITERATURE REVIEW

Climate change and the expansion of beavers

Beavers are ecosystem engineers whose northern range extent is thought to be limited by the availability of woody habitat and a constant water source during the winter months (Busher, 1996; Gallant et al., 2004; Gurnell, 1998). Climate change and the shrubification of habitats beyond the treeline are hypothesized to be facilitating beaver colonization of tundra ecosystems, resulting in beaver re-engineering of tundra riparian habitats (Jarema, 2006; Jones et al., 2020; Jung et al., 2017; Tape et al., 2018; Tremblay et al., 2012). Beaver damming activities can dramatically alter the environment and transform stream systems into wetlands, modifying the morphology, hydrology, chemical composition, and species composition of the stream (Collen & Gibson, 2000; Kemp et al., 2012; Macfarlane et al., 2017; Naiman et al., 1988). The following literature review focuses on the impacts of expanding beaver populations in tundra regions, including their impacts on rivers, fish, biodiversity and people.

The positive and negative impacts of beaver activities are receiving unprecedented attention in mainstream media as researchers, journalists, and nature enthusiasts broadcast conflicting messages through news outlets, documentaries, radio shows, and publications. A recent wave of media attention focused on beaver expansion into the Arctic, based predominantly on research conducted in Alaska (Jones et al., 2020; Tape et al., 2018), includes alarming titles such as “Beavers Emerge as Agents of Arctic Destruction” (Pierre-Louis, 2017), “Beaver invasion in the Arctic is melting ice and ‘making global warming worse’” (Pettit, 2020), and “Beavers are gnawing away at the Arctic permafrost, and that's bad for the planet” (Hunt, 2020). In the words of New York Times journalist Kendra Pierre-Louis: “…as the beavers head north, their very presence may worsen the effects of climate change. The issue isn’t just that the beavers are moving into a new environment – it’s that they’re gentrifying it” (Pierre-Louis, 2017). These ominous headlines and predictions come at the same time as others are touting the importance of beavers in fighting climate change, improving incised river systems, protecting threatened or endangered species, and restoring balance to many of the world’s ecosystems through “rewilding” (Bailey et al., 2019; Bouwes et al., 2016; Dittbrenner et al., 2018; Goldfarb, 2018a;

Pollock et al., 2014; Rosell et al., 2005; Ward & Prior, 2020). In his book "Eager: the surprising, secret life of beavers and why they matter", Ben Goldfarb (2018b) goes so far as to accuse the New York Times article by Pierre-Louis of "castorphobia", saying that humans need beavers in order to revive biodiversity and combat the impacts of climate change and resource depletion by humans.

The intent of this review is to synthesize available scientific literature and position this evidence in relation to concerns over potential negative impacts of beavers within tundra systems, by asking how these two conflicting messages can be reconciled. The focus of this review is the North American beaver (*Castor canadensis*), however some examples come from literature about the Eurasian beaver (*Castor fiber*), as the impacts of both species are very similar (Collen & Gibson, 2000; Rosell et al., 2005). This question will be explored from four facets: the impacts of beavers on water bodies and permafrost, the impacts of beavers on fish species, the impacts of beavers on general biodiversity in the Arctic, and the impacts of beavers on people.

1) Beaver impacts on water bodies and permafrost

1.1) Below the treeline

Beaver damming activities have different impacts on water systems depending on the number of dams, the size of the dams, and the surrounding habitat type (Naiman et al., 1988). In general, beaver dams alter the hydrology of a stream by creating wetlands, raising the water table, storing water, and slowing the flow of water (Collen & Gibson, 2000; Naiman et al., 1988; Pollock et al., 2003). During intense rainfall, beaver dams can attenuate flooding and reduce erosion by allowing excess rainfall to enter groundwater (Collen & Gibson, 2000; Pollock et al., 2003). This capacity to store water may even allow beaver damming to mitigate the impacts of drought events and convert intermittent streams into streams with a perennial flow (Collen & Gibson, 2000; Pollock et al., 2003). Thus, aside from the initial flooding event caused by dam formation and the final flooding event when the dam bursts, beaver ponds have the capacity to regulate water levels in a manner that minimizes the impact of droughts and floods on the areas they occupy (Bylak et al., 2014; Gibson & Olden, 2014; G. A. Hood & Bayley, 2008).

Beaver damming activities also have the capacity to store sediment, promote aggradation, retain nutrients, and alter water chemistry (Brazier et al., 2021; Ecke et al., 2017; Puttock et al., 2018). Overgrazing by livestock may cause streams to cut into the ground and lower the water table, which creates incised streams, decreased groundwater, and a dry floodplain (Pollock et al., 2003). In this context, the capacity of a beaver dam to slow the water, increase the sediment, and raise the stream bed can allow the replenishing of groundwater and nourishment of the floodplain. Thus, beaver dams can restore areas that have been under drought, overgrazed, and eroded (Pollock et al., 2014). Dams may provide an additional ecosystem service by storing excess nutrients, such as nitrogen and phosphate, released from agricultural lands (Lazar et al., 2015; Margolis et al., 2001; Puttock et al., 2017). However, these impacts are dependent on the context, age of the beaver dams, and extent of damming activities (Brazier et al., 2021).

Research on temperature regime changes in areas of beaver colonization has yielded highly varied conclusions (Kemp et al., 2012). Many studies document an increase in temperature associated with beaver damming activities, mainly associated with early pond formation due to an increased surface water area, decreased vegetation cover, and abated stream flows (Collen & Gibson, 2000; Majerova et al., 2015; Margolis et al., 2001). On the other hand, research has also demonstrated that dams do not increase temperatures uniformly but instead reduce daily fluctuations in temperatures and increase spatial heterogeneity of temperatures, which may be beneficial to a variety of species (Rosell et al., 2005; Weber et al., 2017). Temperature trends are highly dependent on the location, impoundment type, age of the dam, and spatial scale of the study (Collen & Gibson, 2000; Stringer & Gaywood, 2016). In a time when extreme weather events such as droughts and floods are becoming increasingly frequent and destructive, beaver regulation of flow rates and water levels has been identified as an ecosystem process that might mitigate these events (Dittbrenner et al., 2018; G. A. Hood & Bayley, 2008).

1.2) Above the treeline

In the Arctic, environmental conditions are becoming more unpredictable, droughts are becoming more common, and the ground is lifting through the process of isostatic rebound (Hassol, 2004; Neelin, 2021; Power & Barton, 1987). In this context, the potential of beaver dams to store water and attenuate droughts and floods would, in theory, offer an important regulating ecosystem service. However, these theoretical benefits have not been documented on the ground by the few research publications on the topic (Jones et al., 2020; Tape et al., 2018). To date, the biggest impacts of beaver damming activities on tundra landscapes seem to be an increase in surface water area and the thawing of permafrost, with these two outcomes closely linked (Jones et al., 2020). The initial flooding event during dam creation allows water, which is warmer than soil, to come into contact with permafrost and trigger its degradation (Jones et al., 2020; Lewkowicz & Coultish, 2004; Tape et al., 2018). In the tundra, permafrost is the structural backbone of the land: the permanent ice that holds the soil together (Woo et al., 1992). Permafrost thaw can cause erosion and ground collapse (Power & Power, 1995; Thienpont et al., 2013), creating depressions into which more water can flow, leading to further permafrost degradation and soil collapse in a positive feedback loop which can create or add to thermokarst landscapes (Jones et al., 2020; Tape et al., 2018; Woo et al., 1992). Beaver dam failure has also been associated with the increased draining of lakes, a phenomenon that has already been observed and documented through satellite imagery and local observations (Hinkel et al., 2007; Jones et al., 2020). Thus, above the treeline, the varied impacts of beaver on water bodies are further complicated by interactions with permafrost.

Although in many cases beaver dams buffer water temperature, Tape et al. (2018) predict that in the Arctic beaver damming activities will increase water temperatures during the winter. This is due to the increased depth and decreased ice thickness in this environment, which are also associated with increased temperatures at the water-sediment interface (Arp et al., 2016; Tape et al., 2018). This can transform bedfast ice (ice that reaches the lake bed) to a floating ice regime (ice above liquid water) and change evaporation and ice-out timing (Arp et al., 2015; McNamara & Kane, 2009; Tape et al., 2018).

The impacts of beavers on landscapes and water bodies in tundra versus temperature forest biomes are not directly comparable because the presence of permafrost makes the Arctic uniquely vulnerable. Research documenting beaver impacts on Arctic landscapes and water bodies is very limited and many projections are speculative, yet the possible implications for Arctic lands and waters are dramatic.

2) Beaver impacts on fish species

2.1) Below the treeline

A meta-analysis on the impacts of beavers on fish species performed by Kemp et al. (2012) identified 108 articles published from 1935-2012 that discussed interactions between beavers and fish. Positive impacts were reported 184 times while negative impacts were reported 119 times. Beaver activity impacts fish species through their alteration of stream depth, complexity, current, dissolved oxygen levels, nutrient composition, and temperature. Fish native to beaver-populated areas tend to benefit from the presence of beavers due to the provision of a complexified habitat, regulated water flow, increased numbers of invertebrates, temperature refuges, and sheltered areas (Kemp et al., 2012; Pollock et al., 2003).

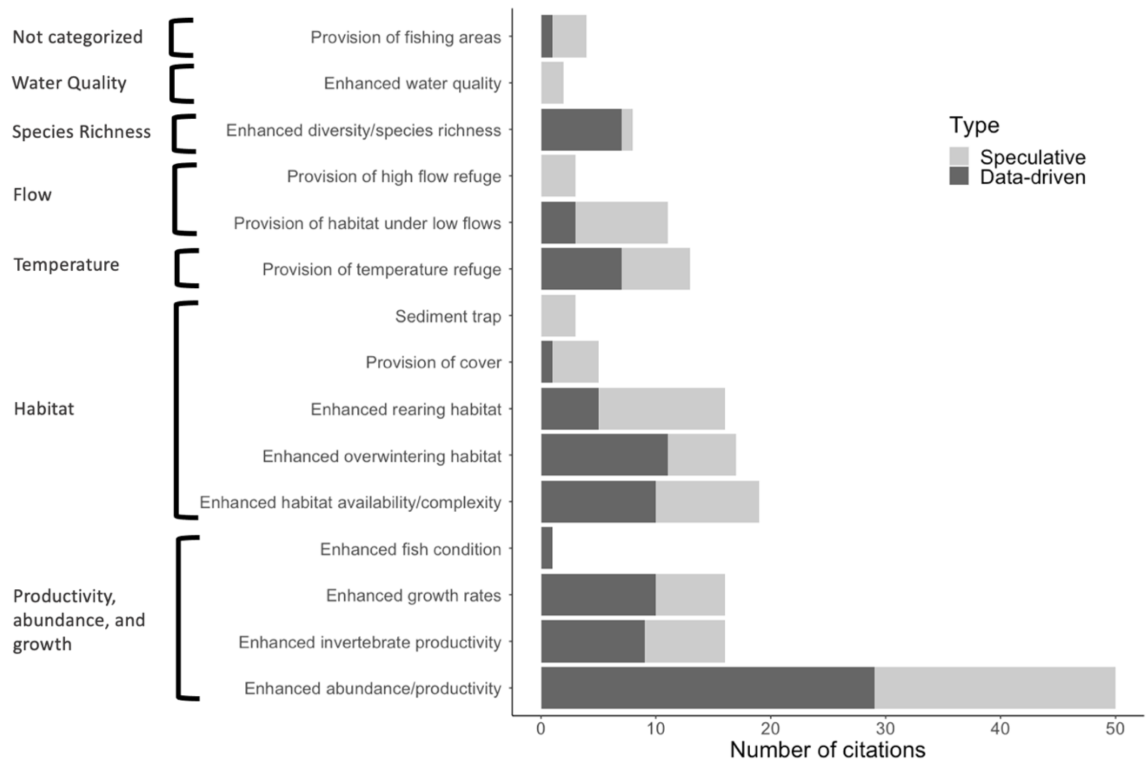

Figure 1. Positive impacts of beaver activity on fish, as reported in 108 literature sources reviewed and classified as data-driven (based on quantitative analysis) or speculative by Kemp et al. 2012. Figure is based on data presented in Table 2, pp. 164, and categories of impact described in the literature review, pp. 163-171, of Kemp et al. 2012.

Temperature refuges include enhanced overwintering habitat for many fish species by stabilizing thermal conditions, lowering current velocity, and creating areas of floating ice in previously shallow, bedfast ice conditions (Chisholm et al., 1987; Kemp et al., 2012; Lindstrom & Hubert, 2004; Tape et al., 2018). This can allow fish to extend into habitats where they were not previously able to survive.

Beaver dams can increase the overall biodiversity of fish species in an area as well as encourage faster growth, larger sizes, and higher abundance of some species (Pollock et al., 2003; Snodgrass & Meffe, 1998). Beaver re-introductions and beaver dam analogs have been effectively used as management strategies for fish habitat restoration (Bouwes et al., 2016; Pollock et al., 2014).

The most highly cited negative impacts of beavers on fish, according to the review by Kemp et al. (2012; Figure 2), was the barrier that dams created to their movement. Although most (78%) such studies were speculative (as opposed to data-driven), those authors argued that dams may reduce fish access to spawning areas or potential new habitat.

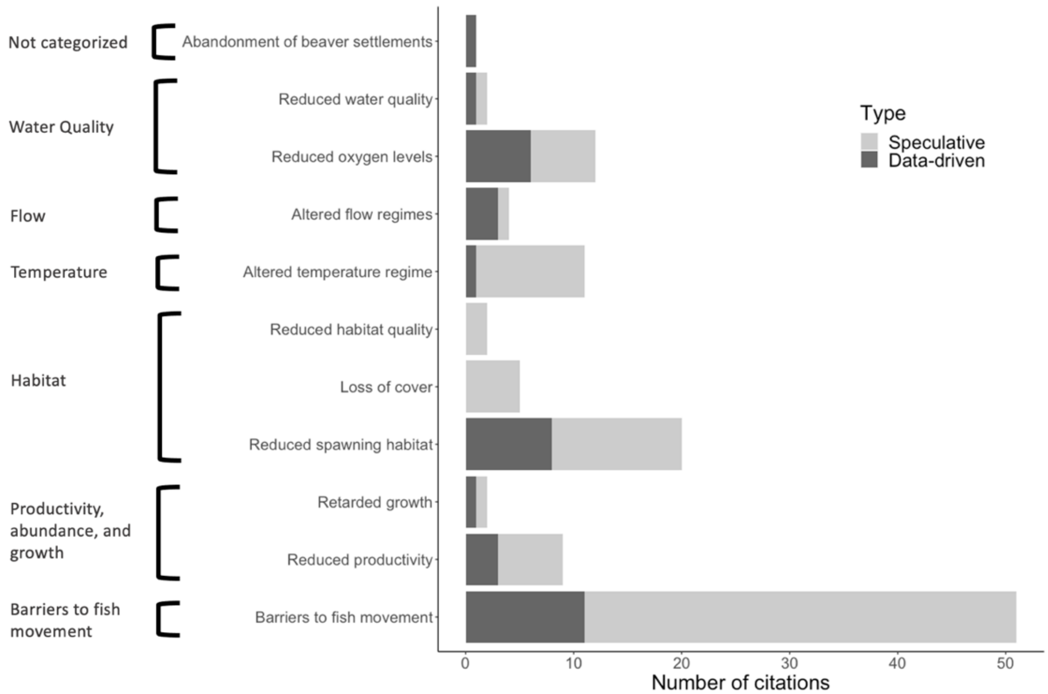

Figure 2. Negative impacts of beaver activity on fish, as reported in 108 literature sources reviewed and classified as data-driven (based on quantitative analysis) or speculative by Kemp et al. 2012. Figure is based on data presented in Table 3, pp. 164, and categories of impact described in the literature review, pp. 163-171, of Kemp et al. 2012.

Many fish that are native to beaver ranges are able to pass dam structures by leaping over dams, using relief channels, waiting for high flows, or wriggling through the dam itself. Relief channels built by beavers during periods of high flow may allow more fish to pass the dam (Bylak et al., 2014). Fish are less able to pass dams on small tributaries and during periods of low flow (Bylak et al., 2014; Kemp et al., 2012). Thus, beaver dams may be a temporary or permanent barrier to some fish but not others, depending on the type of fish, the environmental conditions, the type of dam, and the placement of the dam (Bylak et al., 2014; Lokteff et al., 2013). A study by Lokteff et al. (2013) demonstrated that native trout were much better at navigating dams than non-native trout. Other cited negative impacts of beaver on fish include decreased spawning habitat, lowered oxygen levels, and thermal effects such as warmer water temperatures (Kemp et al., 2012).

2.2) Above the treeline

Fish species present in tundra regions may be less well adapted than southern species to the dams and water conditions associated with beaver presence (Malison et al., 2014; Moerlein & Carothers, 2012). The overwintering habitat and floating ice conditions created by beavers could be helpful for Arctic species by increasing the number of potential overwintering sites (Lindstrom & Hubert, 2004; Pollock et al., 2003; Tape et al., 2018). However, it is unclear what impact beaver-altered temperature regimes might have on their spawning habitat and productivity; Arctic species such as the Arctic char (*Salvelinus alpinus*) and Dolly Varden (*Salvelinus malma*) have a very specific thermal requirement for spawning, which offers a competitive advantage in colder regions (Doidge & Power, 2013; Jensen et al., 1989; Moerlein & Carothers, 2012; Power et al., 2012). Climate change has been already been predicted to cause the reduction of Arctic char, Dolly Varden, and whitefish (*Coregonus spp.*) populations or their replacement by species such as Pacific salmon (*Oncorhynchus spp.),* Atlantic salmon (*Salmo salar*), brook trout (*Salvelinus fontinalis*), or pike (*Esox lucius*; Moerlein & Carothers, 2012; Power et al., 2012; Reist et al., 2006). Tape et al. (2018) predict increased water temperatures in beaver-formed ponds above the treeline during winter; a thermal shift that may disadvantage some Arctic species by reducing spawning habitats and productivity (Doidge & Power, 2013; Moerlein & Carothers, 2012). This effect could be worsened if these changes facilitate the expansion of fish species such as Pacific Salmon, Atlantic salmon, brook trout, and pike, which may increase competition with or predation on more northern species (Moerlein & Carothers, 2012; Reist et al., 2006; Tape et al., 2018).

Arctic char are a key fish species native to many circumpolar Arctic regions, yet to date, there are no scientific publications and only one local knowledge report (Neelin, 2021) that discuss the impact of beavers on Arctic char. Power and Barton (1987) did, however, note the presence of a beaver dam on an Arctic char system as part of a broader survey of potential obstacles to char migration for the purpose of management planning. Anadromous Arctic char migrate every year from the ocean to lakes to overwinter (Finstad & Hein, 2012). The migration happens in a short time frame and the timing is crucial so any obstacle that blocks the migration route may reroute them to a new stream (Grainger, 1953; Power & Barton, 1987). In addition, Arctic char appear less able to leap over obstacles than Atlantic salmon (Grainger, 1953). Although beaver dams may only be a temporary barrier to fish, Arctic char are limited to such a short period of migration that this may impact their access to specific spawning sites (Neelin, 2021). If Arctic char were not blocked by dams, the potential for beavers to maintain water levels and attenuate drought might be considered a net benefit to migrating Arctic char. However, it is difficult to predict the impact of accelerated permafrost melt on water levels and fish movement, since permafrost degradation has also been linked to the draining of lakes or blocking of rivers through landslides or sediment release in some cases (Huscroft et al., 2003; Jones et al., 2020; Marsh et al., 2009; Nitze et al., 2020; Patton et al., 2019; White et al., 2007).

3) Beaver impacts on biodiversity

3.1) Below the treeline

Beavers are the textbook definition of an allogenic ecosystem engineer: an organism that alters the availability of resources for other organisms by physically modifying their habitat (Jones et al., 1994; Wright et al., 2002). By altering their environment, beavers will usually increase overall species richness at both the local scale as well as the landscape scale (Bashinskiy, 2020; Wright et al., 2002). Beaver activities, including felling trees, building dams, and developing canals, increases habitat heterogeneity and species diversity, which, according to Dittbrenner et al. (2018), builds ecosystem resilience in the face of climate change (Brazier et al., 2021; Grudzinski et al., 2020; Hood & Larson, 2015; Wright et al., 2002).

By felling trees, beavers allow sunlight to penetrate forested areas and encourage the growth of low plants, accelerating the process of succession and creating a more varied mosaic of vegetation, especially amongst herbaceous plants (Anderson et al., 2009; Naiman et al., 1988; Stringer & Gaywood, 2016; Wright et al., 2002). By building dams, beavers form ponds and swamps, creating lentic areas amidst a lotic habitat (Andersen & Shafroth, 2010; Anderson et al., 2009; Snodgrass & Meffe, 1998). Beavers introduce a lot of woody material into the water, which increases the level of dissolved organic carbon and, consequently, lowers dissolved oxygen (Rozhkova-Timina et al., 2018). Dam building and flooding activities capture and accumulate sediment from the stream system and alter the chemical composition of the stream (Cirmo & Driscoll, 1993; Collen & Gibson, 2000; Naiman et al., 1988; Pollock et al., 2003; Rozhkova-Timina et al., 2018). This creates distinct habitats in multiple sedimentary layers throughout the pond, as well as above and below the dam, so that a greater number of species with diverse habitat requirements can occupy the same space (Johnston & Naiman, 1987; Stringer & Gaywood, 2016).

Bacterial plankton, zooplankton, and aquatic invertebrate species generally increase near beaver construction sites, but the community structure changes to favour those that thrive in lentic areas (Bylak et al., 2014; Elmeros et al., 2003; Law et al., 2019; McCaffery & Eby, 2016; Naiman et al., 1988). Amphibians such as frogs, salamanders, toads, and newts usually flourish in beaver ponds, often preferring such habitat for reproduction (Elmeros et al., 2003; Janiszewski et al., 2014; Stringer & Gaywood, 2016). Of the reptiles, turtles generally profit the most from beaver ponds, but lizards and snakes can also increase in those areas (Janiszewski et al., 2014). Birds often benefit from the habitat complexity and invertebrates available at beaver sites, as well as varied nesting sites, which may include dead trees (Elmeros et al., 2003; Gibson & Olden, 2014; Rozhkova-Timina et al., 2018). Mammals may also benefit; herbivores from restored meadows with healthy grasses and sedges, insectivores from the diversity of insects, predators from prey that are attracted to these areas, and many mammals from the provision of new shelter areas and the abundance of aquatic invertebrates (Bashinskiy, 2020; McCaffery & Eby, 2016; Rozhkova-Timina et al., 2018).

The species that benefit from beaver sites may change over time as the beaver pond goes through its natural succession (Bylak et al., 2014; Naiman et al., 1988). From early flooding, to ageing, to the collapse of the dam, and even in the marshes, bogs and/or wetlands that follow, each stage in the beaver pond life cycle will offer conditions that may be favourable to different species (Bonner et al., 2009; Ecke et al., 2017; Naiman et al., 1988). Although overall species richness may increase, this does not apply to every organism or to every stage of the beaver pond's life cycle (Naiman et al., 1988). In addition, the impact that beavers may have on the species diversity of a specific area will depend on what was present before their arrival (Johnston & Naiman, 1987). In lakes, beaver infrastructure can help to conserve the ecosystem that is already present rather than replacing it (Bashinskiy, 2020). In arid regions, beavers can raise the streambed and restore biodiversity to areas that have been under drought, overgrazing, and erosion (Gibson & Olden, 2014; Pollock et al., 2014).

3.2) Above the treeline

Many southern animal species are already expanding their ranges northwards, exploiting the opportunities that come with climate change. Aside from beavers, moose and snowshoe hares are two examples of species in Alaska that have been profiting from the process of shrubification, the increasing shrub cover and height in the tundra landscape (Tape, Christie, et al., 2016; Tape, Gustine, et al., 2016). Beavers should initially decrease shrub cover through their foraging activities, but over time Tape et al. (2018) predict that shrub cover will become higher and denser near beaver ponds because their ponds accelerate permafrost erosion, which can create retrogressive thaw slumps (RTS), which can facilitate seedling recruitment and accelerate shrubification (Huebner & Bret-Harte, 2019). Although these shrubs provide food for Arctic species such as ptarmigan, they also assist southern species such as moose to expand to new areas (Jung et al., 2017; Tape et al., 2018a; Zhou et al., 2020). Increases in erect shrub cover reduces lichen cover, which decreases habitat quality for caribou and causes them to shift to less-suitable winter diets, including shrubs (Fraser et al., 2014; Joly et al., 2009).

In his popular book, Ben Goldfarb describes the potential beavers have to help the world adapt to climate change: "beaver-created channels and wetlands may someday help moose, songbirds, and other northward-fleeing species adapt to global warming" (Goldfarb, 2018b). Urban (2020) argues that climate-tracking species should be welcomed as climate change "refugees" and that whole ecosystem shifts should be embraced as a form of ecological resilience. On the other side of the debate, popular press introduced the comparison of gentrification (Pierre-Louis, 2017). According to Merriam-Webster, gentrification involves affluent newcomers reshaping a neighborhood in a manner that makes it less livable for its original residents. In this comparison, beavers could be likened to the affluent newcomers, engineering new neighborhoods in the Arctic to better accommodate themselves and their southern friends. The original inhabitants are the Arctic species who are already experiencing the impacts of climate change at a higher rate than the rest of the world. As the southern species move in, the local species may be displaced, which, for Arctic species, may mean habitat loss due to the "Arctic squeeze" effect (Meredith et al., 2019; Turner & Lantz, 2018). These interactions are difficult to predict, however, as many of these future ecological communities lack modern analogs for comparison (Williams & Jackson, 2007).

4) Beaver impacts on people

4.1) Below the treeline

The human-beaver relationship has never been a straightforward one. North America's long history with beavers begins with Indigenous peoples, many of whom continue to live alongside beavers and recognize the important part that they play in the ecosystem (Jenness, 1977). Many Indigenous groups relied on beavers for food and used various parts of the beaver as clothes, blankets, bags and tools (Honigmann, 1954; Jenness, 1977). The arrival of colonizers, beaver hats and the fur trade announced a new era in the human-beaver (and human-human) relationship (Hickerson, 1973; Johnston, 2017; Mackie, 1997; McClellan, 1978). Beavers were over-trapped for trading, populations plummeted, farming replaced their meadows, and the North American landscape as a whole changed dramatically (Mackie, 1997; Müller-Schwarze, 2011; Sturtevant, 1986).

Delving into recent accounts of beaver-human interactions south of the treeline, it is quickly evident that many stakeholders are not enamored by their tree-felling and pond-forming habits (Jonker et al., 2009; Siemer et al., 2013). Although in the long run beavers can minimize drought and flooding events, their initial flooding can cause enough damage to human infrastructure to cause municipal and city officials to prioritize elimination or relocation of the "nuisances", instead of waiting to find out what ecosystem services they might be able to provide (Fountain, 2014; Gibson & Olden, 2014; Müller-Schwarze, 2011; Siemer et al., 2013). Some additional concerns that have been raised about beavers and their impact on humans in the south concern the sicknesses that beavers sometimes bring. Beaver ponds may have *Giardia* cysts, which may cause "beaver fever", diarrhea, fever, and in a few cases even arthritis, if the water is not treated before drinking (Bashinskiy, 2020; Carlson & Finger, 2004).

"Beaver believers" are fighting to change the predominant discourse and recognize the important role that beavers can play in combating climate change and restoring watersheds (Goldfarb, 2018a; Woelfle-Erskine & Cole, 2015). These scientists, journalists, and environmental enthusiasts argue that it is worth the effort to find creative solutions for humans to cohabit with beavers in order to benefit from their ecosystem services. Creative reintroduction programs and beaver analogues in both North America and Europe have helped restore farmlands, save money on irrigation systems, recover incised streams, and increase biodiversity (Andersen & Shafroth, 2010; Bailey et al., 2019; Charnley et al., 2020; DeVries et al., 2012; Fesenmyer et al., 2018; Müller-Schwarze, 2011; Pollock et al., 2014). Drought- and wildfire-prone regions in the western US have benefited from increased water availability and fire resistance offered by beaver-created water storage (Fairfax & Whittle, 2020; Fountain, 2014; Pilliod et al., 2018). Thus, below the treeline, beavers can provide many ecosystem services that will likely become increasingly in-demand as climate change increases the unpredictability of weather events (Dittbrenner et al., 2018).

4.2) Above the treeline

Across the Arctic of Canada and the United States, Indigenous groups are constantly adapting to the impacts that climate change brings. In her book "The Right to be Cold", Sheila Watt-Cloutier describes climate change as a human rights issue; "climate change is about people as much as it is about the earth, and the science, economics and politics of our changing environment must always have a human face" (Watt-Cloutier, 2015). Inuit and other Indigenous groups across the North American arctic are facing new dilemmas, new ice conditions, and new species that they have never before had to deal with (Brubaker, Berner, Chavan, et al., 2011; Falardeau & Bennett, 2019; Ford et al., 2010; Furgal & Seguin, 2006; Hassol, 2004). How will new species, such as beavers, impact their lives?

The effect of beaver ponds on the landscape could impact land-based and water-based travel. The increase in surface water, changes in water levels, and accelerated permafrost degradation may be unexpected to hunters and difficult to foresee or navigate using traditional knowledge and skills (Brubaker, Bell, et al., 2011; Brubaker, Berner, Bell, et al., 2011; B. M. Jones et al., 2020). Consequences of permafrost degradation can include the collapse of roads and paths to access harvesting areas, the draining of lakes, the decrease in structural integrity of structures such as cabins, the reduced availability or quality of drinking water sources, or the collapse of riverbanks, which can block streams with piles of sediment (Chambers et al., 2007; Furgal & Seguin, 2006; Hinkel et al., 2007; Jeff Birchall & Bonnett, 2020; Melvin et al., 2017; White et al., 2007). This can impact the well-being, safety, and traditions of Indigenous populations living in the Arctic.

In Nunavik, Inuit fishers have concerns regarding the challenges Arctic char may have in circumventing beaver dams to reach their overwintering sites (Neelin, 2021). During the short migration period, barriers can cause Arctic char to change systems (Power & Barton, 1987). For Inuit who have traditional ice fishing sites near to their communities, the absence of Arctic char may impact the food that they are able to provide for their families. According to food recall surveys, Arctic char are the second most consumed country food after caribou in Nunavik, with more than three-quarters of respondents consuming char 11 or more times per year (Blanchet & Rochette, 2008; Lemire et al., 2015). If Arctic char decline and/or shift their overwintering habitat due to beaver presence, this could have important implications for Inuit food security.

Moreover, northward expansion of southern fish and land animals is likely to increase interspecific competition with Arctic resident species. Many Indigenous fishermen have preference for traditional fish species and may not appreciate an increase in new fish species, especially if it impacts their traditional fish (Brubaker, Bell, et al., 2011). Although Tape et al. (2018) suggest that northward expansion of salmon in Alaska may provide an important future resource, Inuit in Nunavik shared concerns that salmon may be replacing or displacing Arctic char, which is the preferred species (Neelin, 2021). Similar observations have been made for the introduction of new mammals into the Arctic ecosystem, which may have unforeseen consequences on native species. Gwich'in and Inuvialuit residents of the Mackenzie Delta have expressed concern over increases in otter and beaver populations, which may impact muskrat availability, which is their preferred harvest (Turner & Lantz, 2018). Whether it be through competition, habitat changes, or predation, northward expansion of southern species are likely to trigger additional changes to which indigenous groups in the Arctic will be forced to adapt.

Additional concerns raised by Indigenous groups include travel conditions and water quality. In the Northwest Territories, Inuvialuit fishermen have been concerned about beavers because of changes in fish availability at fishing sites, and have also raised concerns about the drying out of water bodies, aggravated travel conditions, and decreases in water quality related to beaver establishment (Heredia Vazquez, 2019; Wangkhang, 2017). In Alaska, hunters from the communities of Kivalina and Noatak brought up concerns about *Giardia* in their water, which they now have to boil while hunting (Brubaker, Bell, et al., 2011; Joling, 2011).

These are new and unfamiliar concerns for Indigenous groups. More collaborative research is required in order to prepare effective mitigation and adaptation strategies, so that Indigenous groups can continue to harvest healthy food and support their families amidst rapid and daunting changes (Ford, 2009).

Generalizing beaver impacts above and below the treeline

In areas where beavers are "native" [1] and other species have evolved alongside them, it seems clear that beavers can regulate and clean water, promote biodiversity, and combat extreme weather events. This is tremendously important for the resilience of remote, rural and peri-urban landscapes in the face of climate catastrophes. However, beavers are not planning and engineering these landscapes to benefit the greater good. In the words of Woelfle-Erskine and Cole (2015), "through their daily actions, they inadvertently create the conditions for many other species' flourishing." Beavers are trying to live their beaver lives, provide food for their families, and stay sheltered from predation, and they just happen to create fortuitous by-products from their labour that may help other species. Woelfle-Erskine and Cole go on to say, "Beavers are not ecosaviors who can magically restore a right ecology or an unfragmented landscape. [...] The

[1] The term "native range" can be ambiguous, for more see Pereyra (2020).

beavers' novel ecosystems will incorporate vestiges of large dams, edges of cityscapes, road culverts—and may sometimes promote species undesirable for native species [...]. Beavers do not recognize native/nonnative boundaries any more than they recognize human settlers' property lines." In Arctic environments where they are a new species, beavers are still trying to achieve the same goals as below the treeline: stay well-fed and keep their families safe. The fact that their changes may amplify the impacts of climate change in the tundra is an unfortunate by-product. And although their activities may aid "northward-fleeing species" (Goldfarb, 2018b), it may come at a cost to Arctic residents (Meredith et al., 2019; Urban, 2020).

Many of the foreseen consequences are speculative because the expansion of beavers into the Arctic is a new phenomenon and the available body of research on this topic is very limited. Indigenous groups and governing bodies are forced to make major management decisions based on incomplete information. Further research is required to provide better evidence and more clarity to this complex impact.

Indigenous Knowledge and Community-based Monitoring

There is considerable overlap in the literature between definitions of community-based monitoring and traditional and local ecological knowledge, and a multitude of acronyms used for both (Gofman, 2010). Community-based monitoring broadly refers to observations made by local residents, repeatedly over time, and focused on the local environment and species, but specific definitions vary (Gofman, 2010; Johnson et al., 2015). While community-based monitoring tends to focus more narrowly on observations, Indigenous knowledge is, more broadly, a way of knowing, which transcends facts and observations to encompass values, culture, and world-view (Wenzel, 2004). Traditional and local ecological knowledge specific to Inuit is most appropriately referred to as Inuit knowledge or Inuit Qaujimajatuqangit (Pedersen et al., 2020; Wenzel, 2004).

Habitat Use and Selection

Habitat selection refers to the choice of environmental resources that animals make, which is driven by factors such as foraging, cover, predation, and denning site availability (Krausman, 1999; Morrison et al., 1992). Habitat can be defined as the physical and biological resources or conditions that are important to an organism for its survival and reproduction (Hall et al., 1997; Morrison et al., 1992). Habitat requirements, including for food and cover, are species-specific (Morrison, 1992). Habitat selection is a scale-dependent and hierarchical choice that organisms make among alternative habitats that are available (Johnson, 1980). It can be analyzed at a biogeographic scale (what habitat features correspond to the species' range?), a landscape scale (what habitat features correspond to where most individuals occur?), and a local scale (what habitat features correspond to the specific locations and behaviour of individual animals?; Morrison et al., 1992). Additional considerations in habitat selection analyses include the spatial configuration of habitats on the landscape, the independence of observations given strong temporal and spatial autocorrelation in most wildlife and habitat data, and the reality that habitat selection, like the multidimensional niche, is multivariate and usually requires non-linear analyses of a combination of categorical and continuous variables (Morrison et al., 1992).

Research opportunity and approach

A prerequisite to assessing the impacts and effectively managing climate-tracking species, is a thorough understanding of their historical and present-day distribution and habitat use. Beaver distribution may be revealed through community-based monitoring (Johnson et al., 2015; Kouril et al., 2016), traditional and local ecological knowledge (Brook & McLachlan, 2008), helicopter surveys (Jarema, 2006; Smith & Tyers, 2012), remote detection of dams and flooding through satellite images (Tape et al., 2018), or mixed-methods approaches. Community-based monitoring and Inuit knowledge may help elucidate the impacts of beaver presence on the ecosystem by comparing historical trends to contemporary realities (Moller et al., 2004), understand impacts on whole species assemblages (Berkes et al., 1994, 2007), capture unusual species interactions (eg. indirect interactions between beavers and beluga; Huntington et al., 1999), and describe beaver impacts on culture and local harvesting activities. Landscape-scale modifications due to beaver damming may also be captured from remote imagery (Henn et al., 2016; Jones et al., 2020), whereas specific wildlife interactions often require time- and energy-consuming sampling methodology (Lokteff et al., 2013; McCaffery & Eby, 2016; Snodgrass & Meffe, 1998), and may be less effective for evaluating long-term interactions when compared to community-based monitoring and Inuit knowledge methods. Habitat selection analyses may enhance research on beaver distribution and impact by concentrating research and management efforts, particularly because monitoring in the Arctic is costly and logistically challenging (Christensen et al., 2020). Beaver habitat use varies depending on spatiotemporal scale and ecological setting (Hood, 2020; St-Pierre et al., 2017; Touihri et al., 2018), thus, habitat selection south of the treeline cannot be directly applied to areas north of the treeline, especially since the harsh winter and lack of trees may be limiting to their survival (Aleksiuk & Cowan, 1969; Jarema, 2006). The research approaches mentioned here can provide insights into the drivers, patterns, and consequences of beaver range expansion above the treeline. These are fundamental research questions that can help direct and inform local management strategies.

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CHAPTER 1: INUIT KNOWLEDGE AND AERIAL SURVEY OBSERVATIONS OF THE DISTRIBUTION AND IMPACT OF BEAVERS IN NUNAVIK

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Abstract

Climate change and the shrubification of the tundra is facilitating the northward range expansion of boreal species into the Arctic. Inuit harvesters have been voicing their concerns regarding increasing populations of beavers (*Castor canadensis*) in Nunavik and their impact on country food species. Here we describe Inuit knowledge and aerial survey observations of the historical and contemporary distribution of beavers in Nunavik, their impacts on harvesting, and potential management strategies. Interviews conducted with 57 respondents from six Nunavik communities indicated the earliest observations of beavers in the Ungava region of Nunavik occurred near Kangiqsualujjuaq in the late 1950s and near Kuujjuaq in the 1970s, with beavers becoming more common close to Tasiujaq beginning in 2000, and recent observations confirming beaver presence much farther north near Aupaluk and Kangirsuk. The impacts of beaver dams on Arctic char migration were identified as a primary concern of Nunavimmiut harvesters and wildlife management organizations. Questionnaires completed by 26 residents of the community of Tasiujaq indicated that perceptions of beavers were mostly negative or neutral, with positive views associated with the use of furs for clothing. Many respondents had very little knowledge of beavers, had never tasted beaver meat, and were uncertain or unsupportive of including beaver meat in their diet, since traditional country food is greatly preferred. Helicopter surveys flown along 867 km of waterways north and south of treeline in the western Ungava region confirmed the presence of beaver sign in 109 locations, including 78 active sites and 31 inactive sites. Management recommendations focused on encouraging beaver trapping through financial incentive and knowledge-sharing with Cree and the creation of working groups focused on Inuit-led beaver research and management.

Introduction

Climate change is disproportionately impacting Arctic regions and Inuit are often among the first to witness and experience the effects of rising temperatures (Cuerrier et al., 2015; Meredith et al., 2019; Riedlinger & Berkes, 2001). Inuit knowledge, or Qaujimajatuqangit, is a dynamic understanding of the world that is shaped by values and culture but is not limited to what is historically familiar (Pedersen et al., 2020; Wenzel, 2004). In the context of climate change research, Inuit knowledge offers experience and knowledge that can inform policy, improve adaptation decisions, and increase resiliency (Downing & Cuerrier, 2011; Riedlinger & Berkes, 2001). It is imperative to include community observations of wildlife and environmental change, together with the broader Inuit knowledge defining the context and significance of these observations, in research and policy focused on climate change and the threats that are faced by Inuit in an era of rapid change (Ford et al., 2010; Hovel et al., 2020; Peacock et al., 2020).

A striking impact of climate change in the Arctic is the northward range expansion of southern species (Meredith et al., 2019). Increased productivity, widespread shrubification, and shifting flora composition has led to borealization of the Arctic (Fossheim et al., 2015) and facilitated the spread of southern vertebrates into tundra biomes (Meredith et al., 2019; Parmesan & Yohe, 2003), including black bears (*Ursus americanus*), moose (*Alces alces*), red deer (*Cervus elaphus*), northern pika (*Ochotona hyperborea*), red foxes (*Vulpes vulpes*), snowshoe hares (*Lepus americanus*) and North American beavers (*Castor canadensis*) (Cuerrier et al., 2015; Elmhagen et al., 2017; Furgal et al., 2002; Safronov, 2016; Tape, Christie, et al., 2016; Tape et al., 2018; Tape, Gustine, et al., 2016). A key Arctic knowledge priority is how the presence of these climate-tracking species might impact local ecosystems and access to country food for Indigenous People (Cuerrier et al., 2015; Elmhagen et al., 2017; Meredith et al., 2019; Wenzel, 2009).

Recent observations of beavers (*Castor canadensis*) in the Arctic are noteworthy because of their ability to modify their environment and the far-reaching consequences that their habitat engineering may have (Brubaker, Bell, et al., 2011; Brubaker, Berner, Bell, et al., 2011; Jarema, 2006; B. M. Jones et al., 2020; Jung et al., 2017; Tape et al., 2018). Remote sensing studies conducted in Alaska have documented dramatic increases in beaver dams above the treeline leading to increases in surface water and accelerated permafrost degradation (Jones et al., 2020; Tape et al., 2018). While it is difficult to establish causality, beaver expansion beyond the Alaskan treeline has been attributed to increased habitat suitability due to shrubification and reduced trapping pressures (Tape et al., 2018). Across many Arctic regions, community members have been voicing concerns about the effects of beavers on the Arctic environment, including their impacts on Arctic fish species and drinking water (Brubaker, Bell, et al., 2011; Brubaker, Berner, Bell, et al., 2011). Though these concerns are being communicated locally, including at community meetings and in local news and social media, there is a lack of primary literature describing community concerns about the growing presence of beaver in the Arctic, their impacts on other wildlife and ecosystems, and the management and adaptation alternatives that are being considered or employed. The current study summarizes Inuit and science observations of the historical and contemporary distribution of beavers in Nunavik, their impacts on Inuit country food species, and potential strategies to deter their spread, reduce their impacts, and/or adapt to their presence.

Methods

Study Area

Nunavik is defined as the land of Quebec that lies north of the 55th parallel (Gouvernement du Québec, 1998) and is one of the four regions of Inuit Nunangat, the Inuit-occupied region of northern Canada (Inuit Tapiriit Kanatami, 2018). Fourteen remote Inuit communities lie along the coasts of Nunavik and their inhabitants continue to rely on subsistence harvesting as an important part of their diet, economy, culture, and well-being (Makivik Corporation et al., 2014).

Community engagement

This project began with a knowledge priority discussed by the Nunavik Climate Change Committee on Adaptation (which includes representatives from the Kativik Regional Government [KRG], Makivik Corporation, the Nunavik Hunting Fishing and Trapping Association [NHFTA, also known as Anguvigaq], le Ministère de l'Environnement et de la Lutte contre les changements climatiques [MELCC], and Ouranos) regarding concerns about the impacts of climate change on Arctic char, specifically on stream connectivity for anadromous Arctic char. The committee suggested synthesizing community concerns and recommendations in a report and this project (henceforth referred to as "Arctic char interviews") was taken on by MNN in an internship supervised by Makivik Corporation with the guidance of the Regional and Local Hunting Fishing and Trapping Associations (HFTAs, or Anguvigaq/Anguvigapiit; Neelin 2021). Beaver range expansion and impacts on Arctic char emerged as a local knowledge priority based on concerns raised in Arctic char interviews. A beaver questionnaire and a helicopter survey described below were research activities designed to collaboratively describe and advance this knowledge priority; these were accomplished through continued direction and approval from the Tasiujaq Hunting Fishing Trapping Association (Nanuapiit Board) and input from Makivik Corporation.

Arctic char interviews

Arctic char interviews, and the report in which they are summarized (Neelin 2021), aimed to synthesize concerns about the impact of climate change on Arctic char in general, and in relation to stream connectivity in particular. Interviewees were selected primarily through recommendations from Makivik staff and the Hunting Fishing Trapping Associations (Anguvigapiit) for each of the 10 participating communities, based on their knowledge and ongoing direct experience of the land or of management projects. All Inuk harvesters who requested participation in the consultations were included. Interviews for the internship followed an open-ended question format that began with prompts about Arctic char and climate change and allowed room for the interviewees to express their concerns, even if those deviated from the main questions. Interviews were conducted in English or Inuktitut according to interviewee preference. Results from Arctic char interviews were summarized in the report: "Arctic char in a changing climate: Community priorities and recommendations" (Neelin, 2021). Secondary sources, such as grey literature and unpublished project reports, were evaluated and where appropriate incorporated into the report for an improved understanding of context and past research or management projects. Among the 10 communities interviewed, the subject of beavers was discussed with six communities situated within or close to the current distribution of beavers in Nunavik. Results from those six communities are included in this paper, whereas interview results from Quaqtaq, Ivujivik, Akulivik, and Inukjuak are fully included in Neelin (2021), but not considered here.

During Arctic char interviews and subsequent consultations, many respondents mentioned beaver dams as a barrier for Arctic char migration and were given an opportunity to identify areas where they had seen beaver signs (sightings of beaver dams, lodges, or the animal itself) on a 1:50 000 Canada National Topographic System map of the local region. Years were sometimes, but not often, associated with these sightings. These locally identified beaver sites, which may have been inhabited by beavers recently or in the past, were recorded and used to prioritize survey blocks and transects in the subsequent helicopter survey. Participants from the Hudson coast communities of Kuujjuarapik and Umiujaq shared general information about beaver observations but did not specify map locations of locally identified beaver sites.

Aerial survey

The region surrounding two communities (Tasiujaq and Aupaluk) along the western coast of Ungava Bay was selected as the study area for the helicopter survey due to community interest expressed during the Arctic char interviews, especially from the community of Tasiujaq, and the high number of local beaver sightings in western Ungava. In Nunavik, the treeline extends to southern portions of Ungava Bay, including the mouth of the Koksoak river where the regional capital of Kuujjuaq is located, and approaches but does not reach Tasiujaq, which is located farther north on the western side of Ungava Bay. Thus, the community of Tasiujaq lies just above the treeline while Aupaluk, the community north of Tasiujaq, is surrounded by the tundra ecotone.

The sampling design of the helicopter survey was organized around locally identified beaver sites located in western Ungava, as identified by land users from Tasiujaq, Aupaluk, and Kuujjuaq during Arctic char interviews. Local beaver observations from southern Ungava, around Kuujjuaq and the Koksoak River, were recorded but not incorporated into survey blocks because this area was surveyed in 2004 (Jarema, 2006) and the current survey was intended to focus further north, on the area around treeline in western Ungava. Locally identified beaver sites within western Ungava grouped into two clusters, with one cluster closer to Tasiujaq and the other closer to Aupaluk. The "minimum bounding geometry" tool in QGIS was used to create a boundary around both clusters of beaver sightings, and a 10-kilometer buffer was added to each, to define two survey blocks containing locally identified beaver sites. The Aupaluk Locally Identified (A-LI) survey block was 1073 km^2 and included 8 locally identified beaver sites. The Tasiujaq Locally Identified (T-LI) survey block was 2604 km^2 and included 16 locally identified beaver sites (one locally identified beaver site in proximity to the T-LI block was an outlier, 39.6 km distant from the next closest locally identified beaver site and was omitted to avoid increasing the area of the block by 47% to 3818 km^2). In addition to the two locally identified survey blocks, we selected four systematic survey blocks that were equal in area and positioned adjacent to locally identified blocks. This created three, 2604 km^2 survey blocks around Tasiujaq (T-LI and two adjacent systematic blocks T-A, T-B) and three, 1073 km^2 survey blocks around Aupaluk (A-LI and two adjacent systematic blocks A-A, A-B) with the locally identified blocks (LI blocks) containing locally identified beaver sites and the systematic blocks (A or B blocks) not including locally identified beaver sites.

To identify waterway transects within survey blocks, base maps from the Quebec Government were retrieved as images from the *Forêt Ouverte* interactive map (MFFP, 2019) at 5 km scale and georeferenced in QGIS. These base maps were used because they highlighted the main riparian systems without including all of the small, disconnected thermokarst lakes characteristic of sub-Arctic and Arctic landscapes (Allard & Lemay, 2012; Olefeldt et al., 2016). Within blocks A-LI and T-LI, vector lines ("transects") of 10-15km were drawn along rivers and connected lakes so that all locally identified beaver sites were positioned near the middle of the transects. Once locally identified beaver transects were complete (N=15), transects were drawn along all other river systems (including lakes along river systems) within the block. Each transect was 10 to 15 km long so that all freshwater river systems were covered as completely as possible. Through this process, we identified 114 waterway transects across the 6 survey blocks, including 12 transects summing to 139.5 km in A-LI, 11 transects summing to 143.0 km in A-A, and 11 transects summing to 138.4 km in A-B. Because Tasiujaq survey blocks were larger, T-LI included 24 transects summing to 296.2 km, T-A included 35 transects summing to 456.2 km, and T-B included 21 transects summing to 253.8 km. To keep total survey distance approximately equal between all 6 blocks, while ensuring all locally identified beaver sites were surveyed, we prioritized locally identified transects while also bounding each block to a 136-146 km total survey length range. Accordingly, all identified transects were surveyed in blocks A-LI, A-A, and A-B. For block T-LI, we surveyed all 8 transects that included locally identified beaver sites, hereafter referred to as locally identified transects, plus an additional 4 randomly selected systematic transects. For T-A and T-B we randomly selected transects in each block until the total transect lengths reached 136 km (11 transects for T-A and 12 transects for T-B), and surveyed these as systematic transects within systematic blocks. Thus, locally identified survey blocks include locally identified transects (within which one or more locally identified beaver sites are situated) and systematic transects (lacking locally identified beaver sites), while systematic survey blocks include only systematic transects.

The helicopter survey was conducted during the autumn (31 September 2019 and 1 October 2019) in order to allow for identification of food caches (Hay, 1958). The helicopter followed the planned transects as closely as possible at a speed of approximately 100 km/h and remained approximately 70m above ground level, flying along the left bank of rivers and lakes when the water body widened unless the transect directly crossed the lake to continue following the water system. The pilot and primary observer were both Inuk and additional community representatives and local youth joined for parts of the survey. The pilot and primary observer sat in the front of the helicopter and made preliminary observations of beaver sign, while the secondary note-taker/navigator sat on the rear left seat. When beaver sign was observed, the helicopter circled closer so that the primary observer could confirm the observation, check for any additional nearby sign and take photos of the site, while the note-taker/navigator confirmed the site, classified the sign as active or inactive, and recorded the waypoint.

Active versus inactive sites were distinguished by fresh food caches or by the presence of newly added mud and branches in the lodges and dams (Bradt, 1938; Hay, 1958; Fuller & Markl, 1987).

Beaver questionnaires

A beaver questionnaire was designed to provide additional information about beavers in Nunavik including observations, experience, knowledge, perception, and impact concerns. The Arctic char interviews, described in the previous section, prioritized individuals who were on the land often (or, in the case of Elders, had previously been on the land often) and those recommended by the community were primarily male. The beaver questionnaire was intended to provide a more demographically balanced survey and to be more inclusive of a variety of perspectives, including men, women, and harvesters with varying levels of frequency of time spent on the land. Although concerns about beavers were raised in multiple communities during Arctic char interviews, the Tasiujaq HFTA (the Nanuapiit Board) in particular highlighted beaver impacts as a current knowledge priority. Accordingly, the beaver questionnaire was used to survey Tasiujarmiut (residents of the community of Tasiujaq), who voluntarily completed the written questionnaire with compensation and with the option of assistance. Questionnaires were available in Inuktitut and in English, online or in paper format at the municipal office (Northern Village, or NV), at the Coop store, or brought to their home upon request. Announcements were made over the local radio in Inuktitut, on the community Facebook page, by word of mouth, and posted at the NV and the Coop store. Only Inuit over the age of 18 were allowed to participate, and interview responses made anonymous after ensuring that a consent form had been completed.

The beaver questionnaire included closed-ended questions to describe the respondent and their activity on the land, followed by a some open- and some closed-ended questions about observations of beavers, familiarity with beavers/beaver trapping, perceived impacts of beavers, and interest in beaver meat for consumption. One question asked for respondents to list the first three words, in English or Inuktitut, that came to mind when beavers were mentioned. Phrases were accepted since the structure of Inuktitut condenses a phrase to a single term. Each individual response (phrase or word) was classified as negative, neutral, or positive. For example, phrases explicitly referring to dams as a barrier to fish were considered negative, descriptive words were classed as neutral, and words associated with their utility, such as articles of clothing, were classified as positive. Thus, a single word (eg. “dam”) could be classified differently depending on how it was presented (ie. “dams block Arctic char” would be negative, while “dam” alone would be neutral). Inuktitut terms were translated for analysis except for culture-specific vocabulary that did not have a strong equivalent in English (mainly Inuit clothing articles), which were converted to qaliujaaqpait (Roman orthography) for word cloud analysis. Both English and Inuktitut words were converted to their singular form for text mining (removal of stopwords, punctuation, and whitespace) and the creation of a word cloud, using the “tm” and “wordcloud” packages in R version 4.0.2 (Feinerer & Hornik, 2020; Fellows, 2018; R Core Team, 2021).

Research ethics

Interviews for the Arctic char report were done by MNN under the supervision and guidance of Makivik Corporation and respecting their ethical guidelines. Use of data from these interviews and questionnaire methodology were approved by the McGill University Research Ethics Board Office (REB File #19-10-042). All participants provided written consent for their participation and whether or not they wished to have their names included in reports. Communities were consulted during the drafting process and provided early bilingual (English and Inuktitut) hard copies of the reports so that they could provide feedback. Every participant who was quoted in the final Arctic char report (Neelin, 2021) was consulted individually and permitted to provide additional feedback or edits to their quotes, in Inuktitut as necessary. All quotes mentioned in this paper were originally mentioned in the Arctic char report (Neelin, 2021).

Results

Arctic char interviews

Arctic char interviews included in this study involved seven group interviews, ranging from 2-5 participants, and 32 individual interviews (Table 1). Participants involved in Arctic char interviews were primarily male (51 of 57); one female participant was recommended from Kuujjuaq and five female participants were recommended from Aupaluk. The Aupaluk HFTA highlighted the frequent gender imbalance in research and emphasized the importance of the involvement of women, especially in Inuit knowledge surveys and management decisions regarding fish, since they account for a large proportion of the harvest. Recommended participants were mainly active harvesters, many of whom were involved in elected wildlife management positions and two of whom were also pilots, which extended the spatial distribution of observations. Of the four participants who were not active harvesters, three were involved in wildlife management projects and decision-making and the other was a helicopter pilot whose frequent passage across Nunavik permitted a broad perspective of climate change impacts on Arctic char and species expansion.

Table 1. Contributing communities from Arctic char interviews: Number of group interviews, individual interviews, and total number of participants in each of the communities that participated in this research.

Community	**Number of group interviews**	**Number of individual interviews**	**Total number of respondents**
Kangiqsualujjuaq	2	3	10
Kuujjuaq	0	11	11
Tasiujaq	2	7	11
Aupaluk	1	10	15
Umiujaq	1	0	5
Kuujjuarapik	1	1	5
Total	**7**	**32**	**57**

Participants in these Arctic char interviews identified 118 locally identified beaver sites situated around the communities of Aupaluk, Tasiujaq, Kuujjuaq, and Kangiqsualujjuaq during the initial interviews and during follow-up consultations (Figure 1). In the Ungava region, locally identified beaver sites were particularly common along or near Finger Lake (upriver from Tasiujaq), Koksoak River (upriver from Kuujjuaq), and George River (upriver from Kangiqsualujjuaq).

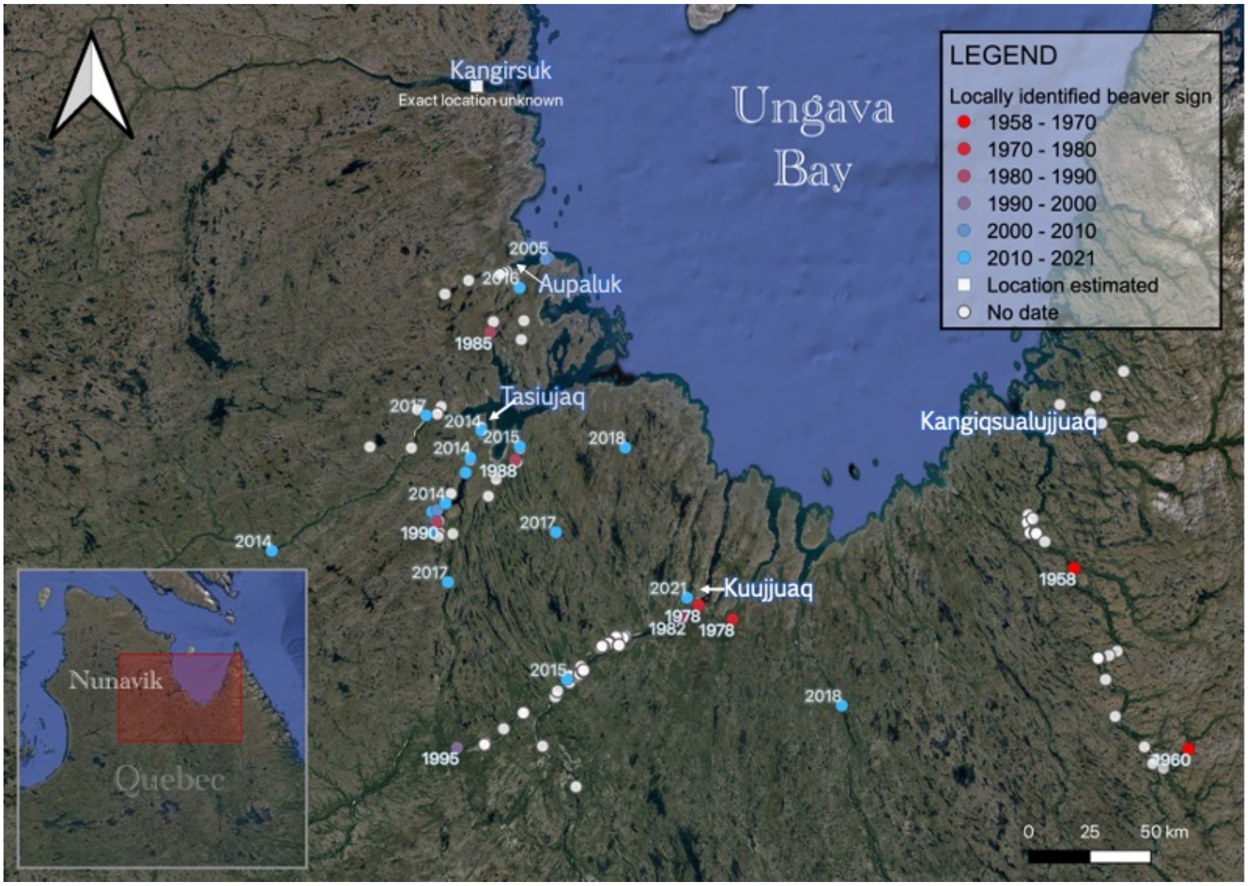

Figure 1. Locally identified beaver sightings in the Ungava region of Nunavik. Year of observation, when available, is indicated numerically and with a red (early) to blue (recent) colour ramp with undated observations indicated in white.

The earliest beaver observations noted by participants were in south-eastern Ungava, around the George River upstream of the community of Kangiqsualujjuaq, in the late 1950s to 1960s.

> You know when I was young, there were no beavers up here. None. You never heard of a beaver. The first ones I started seeing were at Helen's Falls [near Kangiqsualujjuaq]. That was probably 1958. It was bank beavers that were there. And over the years, they seemed to keep multiplying, and there seemed to be a lot of fresh beaver dams, then they'd kind of disappear. The dams would age and I don't know if the population went down or not, but then fresh dams would increase again. This has been progressive over the past 55 years or more. And now there's beavers above the tree line… so they're really spreading. (Johnny May)

Beavers started being observed in south-western Ungava Bay, in areas near Kuujjuaq and the Koksoak River, in the 1970s and began to increase in numbers dramatically soon after. Sightings on Finger Lake and in Tasiujatuqaq, near Tasiujaq, began in the 1980s and 1990s, and the first sighting of a beaver swimming along the shore near Aupaluk occurred in 2005. According to Jarema (2006), a study of beaver presence in Nunavik over a decade ago, Inuit knowledge holders that spoke with the author reported the beaver sighting at the highest latitude along the Ungava Coast to be near Tasiujaq, at a latitude of 58.70°. In 2018, Inuit hunters reported a sighting 72 km north of that, at a latitude of 59.35°. However, one respondent that participated in the Arctic char report shared an observation of a beaver at a latitude of 59.08° (near Ammaluttuq lake) as far back as the mid 1980s (Figure 1), an exceptional observation that was made once from a helicopter survey and was not discussed in the previous study. The beavers seen in that area were harvested and those interviewed did not observe beavers at that latitude again until the 2000s. The most northerly locally identified established beaver sites in the Ungava region were located near Aupaluk, and the most northerly beaver sighting was one swimming in the Payne River, near Kangirsuk (the exact date and location were not provided; Figure 1).

A few participants had explanations for the expansion of beaver populations into Nunavik. Some brought up the increased growth of shrubs, especially willows, a phenomenon termed “shrubification” in recent literature (Myers-Smith et al., 2011).

> [...] Where we’re seeing more beavers maybe is where there were less willows before, but the willows are spreading. So you see they’re moving north, where they can take advantage of food. (Anonymous)

One elder brought up the influence of Hydro-Quebec projects far to the south in James Bay that lowered river depth and reduced habitat quality for beavers in modified reservoirs, forcing them northwards in search of new habitat.

A third explanation offered for the expansion of beaver populations was reduced trapping pressure associated with the relocation and settlement of First Nations groups who had traditionally trapped beavers across northern Quebec, including Nunavik. This observation was shared on the Ungava side, with the formation of Schefferville, as well as on the Hudson coast of Nunavik, with the formation of Whapmagoostui. With the trapping pressure released, and most Inuit lacking the traditional knowledge to trap beavers, populations were able to grow largely unimpeded.

> In the late 1970s, we started to hear of quite a few beavers being noticed here in the river [near Kuujjuaq], which is quite unusual. In the early or mid 1970s, we didn't hear of that. Suddenly it was a dramatic increase of sightings of beavers. People said that they were coming through the main river here, heading north along the shoreline. My mum said, although she wasn't a hunter, her theory was that the inland people (Naskapi people) that were trapping these all the time, had been relocated to Schefferville. So there was no more trapping, and the beaver population has exploded because no one is taking them. (Allen Gordon)

Some of the observations farther north were of beavers swimming along the shore in the saltwater. These observations, from two different participants, were not accompanied by sightings of any structures, such as lodges or dams.

> I've seen them in the ocean, eh? Swimming along the shore. They're not scared to move. […] That's probably why they moved up to Aupaluk. (Anonymous)

Local observations of beaver population expansion during Arctic char interviews were a digression, albeit an educational one, from the main focus of the interviews, which was to synthesize local knowledge, priority, and concerns about climate change impacts on Arctic char. Accordingly, beavers were usually discussed in the context of concerns regarding the impacts of their dam construction activities on this fish species.

Beavers were described as being the climate change threat that has the biggest impact on Arctic char migration near Tasiujaq:

> Beavers and erosion are the biggest impacts that we've seen. Another one is low water, but the biggest I see is the beavers. (James May)

Participants in Tasiujaq and Umiujaq expressed their concerns regarding beaver dams blocking migration routes for anadromous Arctic char more than the other participating communities:

> They have one thing in mind… getting back to the lake. But at times, they divert their migration. That's the problem, 'if I can't get up, I'll go somewhere else'. (Billy Cain)

When Arctic char divert to new lakes, it can result in a decrease in catch at traditional fishing sites or near certain communities.

> I was told before by Elders that during the char migration there should be no obstacles. Once you put obstacles in the water they remember that. (James May)

Umiujaq has experienced a big decline in Arctic char since the 1960s.

> That fish is #1 up north. We used to have a lot [near Umiujaq] in 1940s and 1950s, in 1960s… we don't know where they went. (Anonymous)

> "If those dams were removed, and the bottom of the river was excavated… there would be some possibility for Arctic char to come back [to Umiujaq]." (Anonymous)

Participants in Kuujjuaq also mentioned that some trout, such as speckled trout, were losing access to certain creeks because of beaver damming activities.

Arctic char is one of the best country foods, according to many of the participants. It is very important for Inuit to continue to access this resource for their families. Some communities have experienced rapid declines in Arctic char catches and are concerned that these trends are associated with climate change effects. These effects may include new fish species competing and/or predating on Arctic char or barriers to Arctic char movement such as low water levels, beaver presence, and soil collapse due to permafrost erosion. Interview participants brought up many concerns regarding access to Arctic char in the future, for themselves and for future generations.

Beaver meat, however, is not a staple in Inuit diet, although there are a few people in Kuujjuaq who eat it.

> Some people eat beavers… they're good eh? Like I've eaten them before. But a lot of people won't eat them, like bears. A lot of people won't eat bears here. But if you go where the Cree and the Naskapi are, they hunt bears to eat. So it's more of a habit, I think. People don't eat beavers… but in other places they really like them and it's hard to change habits. (Anonymous)

Communities that participated in the interviews and expressed concerns about beaver presence in Nunavik were asked what research or management they would like to see in the future to deal with these concerns. Research recommendations included determining the distribution of beavers and learning more about their impacts:

> Where are they?! Where are the beavers? That's the main thing. We go out sometimes, but we don't see everything. (David Annanack)

> We need to study beaver dams in the fishing habitats. (Sammy Unatweenuk)

Management suggestions included knowledge sharing with First Nations groups that are more familiar with beaver trapping and preparation. It was suggested that this could be done in a workshop with invited Cree trappers or even with Inuit beaver trappers who live in Kuujjuaq. Many Inuit shoot at beavers when they see them, but this is not a very effective harvesting strategy.

> Find out how many beavers are there and the best way to remove them. It might even come down to hiring Cree or Naskapi people to come and help with the project. We are not traditionally beaver hunters so it's hard trying to trap something that hasn't been around forever, we don't have knowledge of that. (James May)

Interview participants mentioned that many Inuit are still unfamiliar with beavers and that these workshops would help with knowledge transmission from those who are more experienced with this species.

Aerial survey

During the helicopter survey, 72 active and 31 inactive beaver signs were recorded on all planned transects, and an additional 6 active signs were observed while crossing between transects (Figure 2). This included 46 lodges, 22 food caches, 33 dams, and 8 partial dams. The most northerly latitude where beaver sign was observed during the helicopter survey was an inactive dam located at 59.09° N. The most northerly active beaver sign, a lodge, was located at 58.95° N.

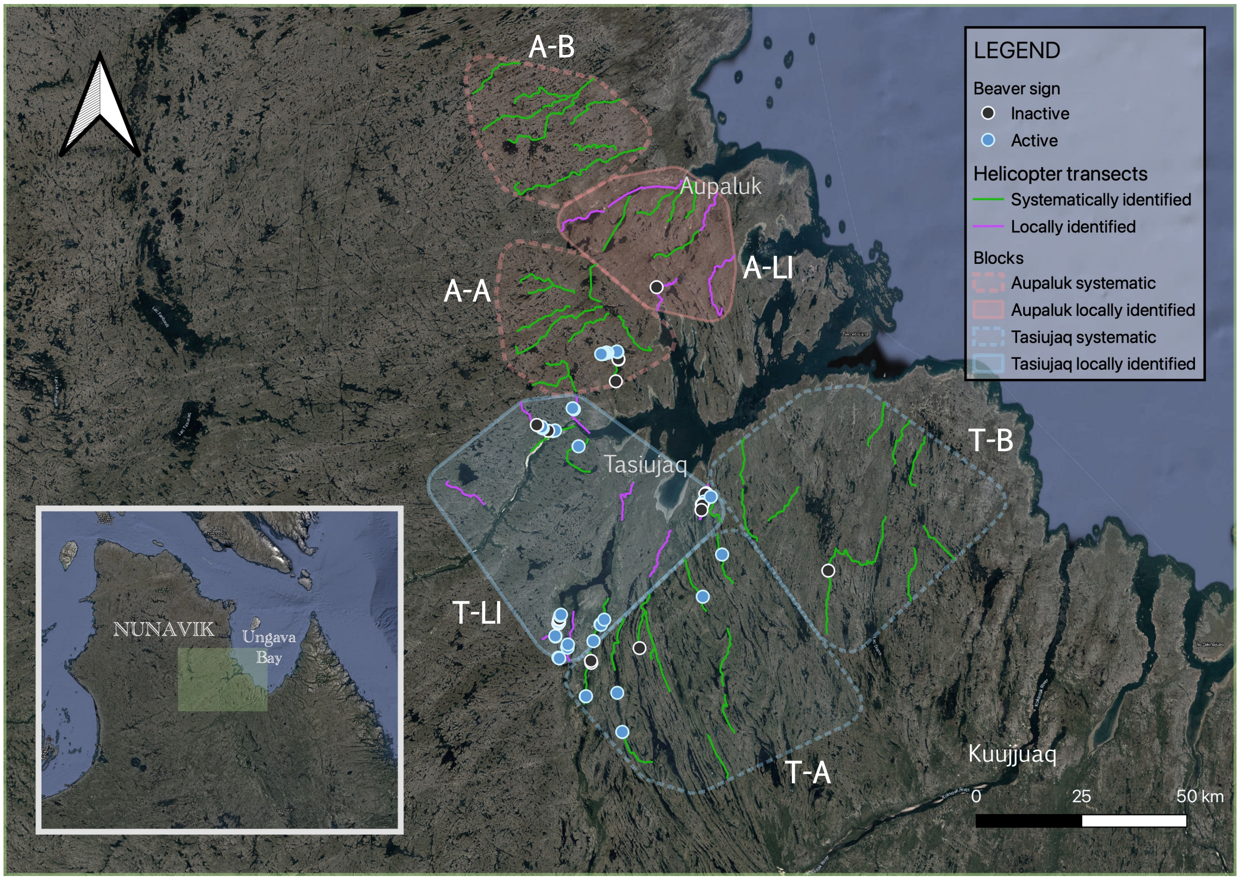

Figure 2. Active (blue) and inactive (grey) beaver sign observed during the helicopter survey of locally identified (n = 15, purple) and systematically identified (n = 54, green) transects. Transects were situated within locally identified (solid line) or adjacent (dashed line) survey blocks. Survey blocks are labeled A- if in proximity to the community of Aupaluk or T- if in proximity to Tasiujaq, with -LI indicating locally identified blocks, and –A or –B indicating adjacent and equal in area survey blocks.

Of locally identified transects, 47% (7 out of 15) had beaver sign observed during the helicopter survey, including both active and inactive signs. Of systematically identified transects, only 17% (9 out of 54) had beaver sign observed during the helicopter survey (Figure 3).

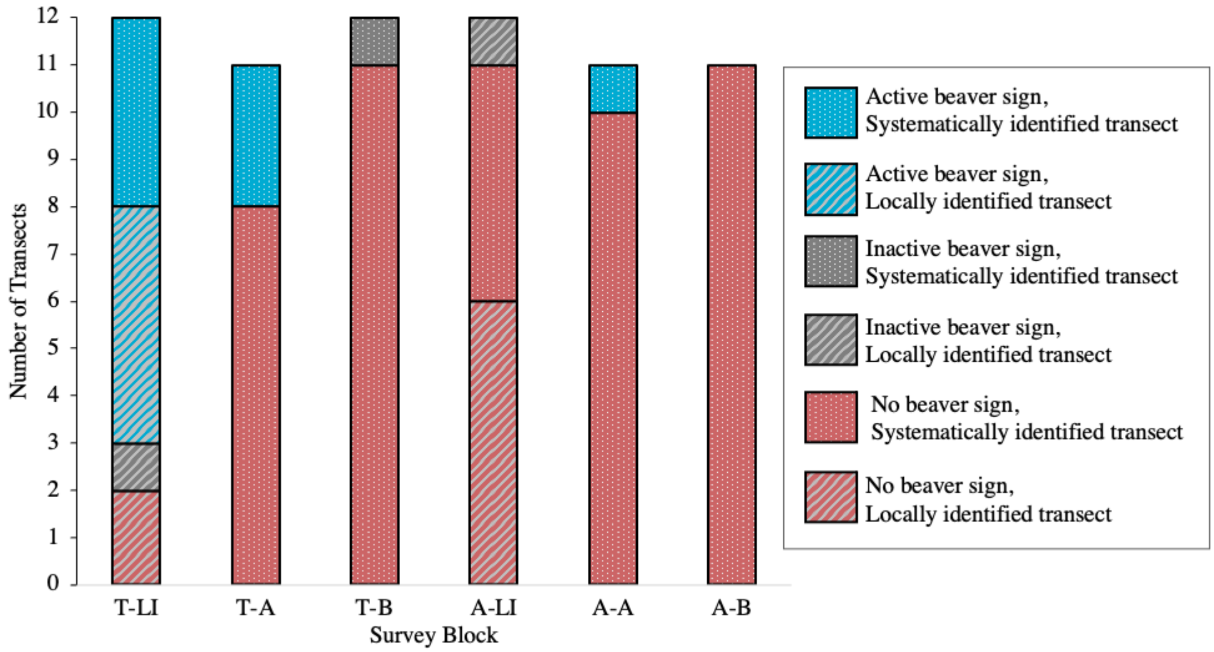

Figure 3. Observations of beaver sign, including lodges, dams, and food caches, along 11-12 transects within six survey blocks. Primary colour indicates total number of transects within each survey block with active (blue), inactive (grey), and no (red) beaver sign observed. Fill pattern indicates whether the transect was based on local observations of recent or past beaver presence (striped) or was a systematic transect where beaver presence or absence was undescribed prior to the survey (dotted). Survey blocks are as described in Figure 2.

Beaver questionnaires

Beaver questionnaires completed by 26 respondents from the community of Tasiujaq incorporated fewer communities and respondents than the Arctic char interviews, but included more gender, age, and experience-on-the-land diversity (Figure 4). Respondents reported diverse experience with hunting or trapping beavers, but more than half (58 %) reported having never hunted or trapped beavers, including among respondents spending considerable time on the land.

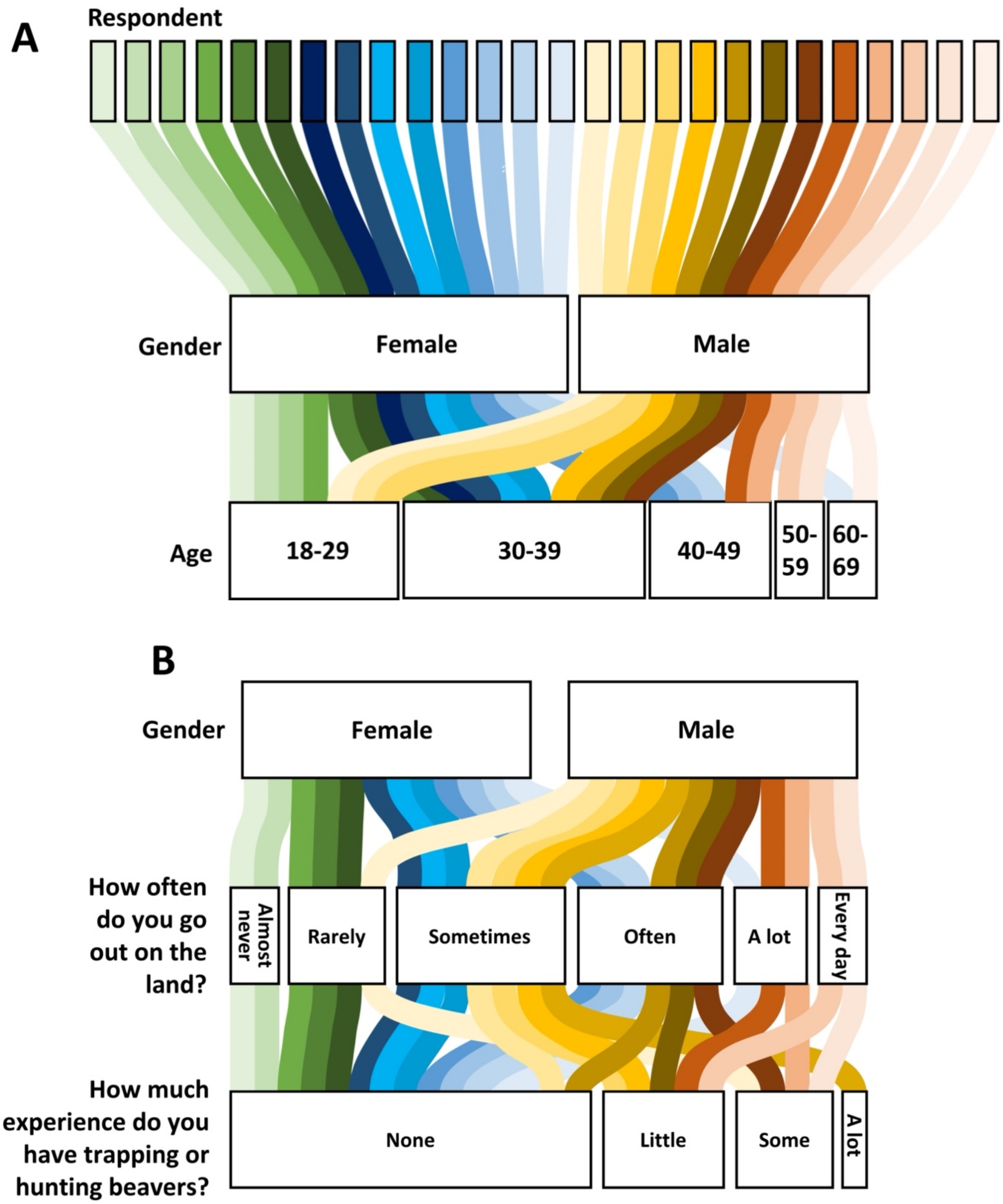

Figure 4. Sankey plot of Tasiujarmiut (Tasiujaq residents) responses to the beaver questionnaire. a) Respondents (indicated by colour) and their gender and age composition. b) Respondents' gender, time spent on the land, and experience trapping or hunting beavers. Time spent on the land was categorized as going on the land every day, a lot (5 or more times per month), often (2-

4 times per month), sometimes (approximately once per month), rarely (2-8 times per year), or almost never (0-1) time per year. Experience hunting or trapping beavers was categorized as a lot (10 or more beavers), some (3-9 beavers), little (1-2 beavers), or none.

When asked to list the first three Inuktitut or English terms that came to mind when thinking of beavers and their impacts, respondents included predominantly negative and neutral words or phrases (90%, or 44 of 49 words/phrases; Figure 5). Women provided mostly neutral words (84%, or 21 of 25 words/phrases), while men provided mostly negative words (75%, or 18 of 24 words/phrases; Figure 5a). Positive words were predominantly related to articles of winter clothing that can be hand-sewn with beaver fur, such as a mitten (pualuk; two mentions), a boot (kamik; 1 mention), a winter hat (two mentions), or the most common positive mention: fur trim on a mitten (quliuti; three mentions; Figure 5b). Negative words were almost exclusively related to the impact of dams on Arctic char migration, and most of the words were extracted from a phrase describing that impact, including river (eight mentions), block (six mentions), fish (five mentions), and dam (two mentions). Exceptions include the words destroy (one mention), shoot (one mention), and kill (two mentions), which are referring to a possible impact management strategy rather than the beaver impact itself.

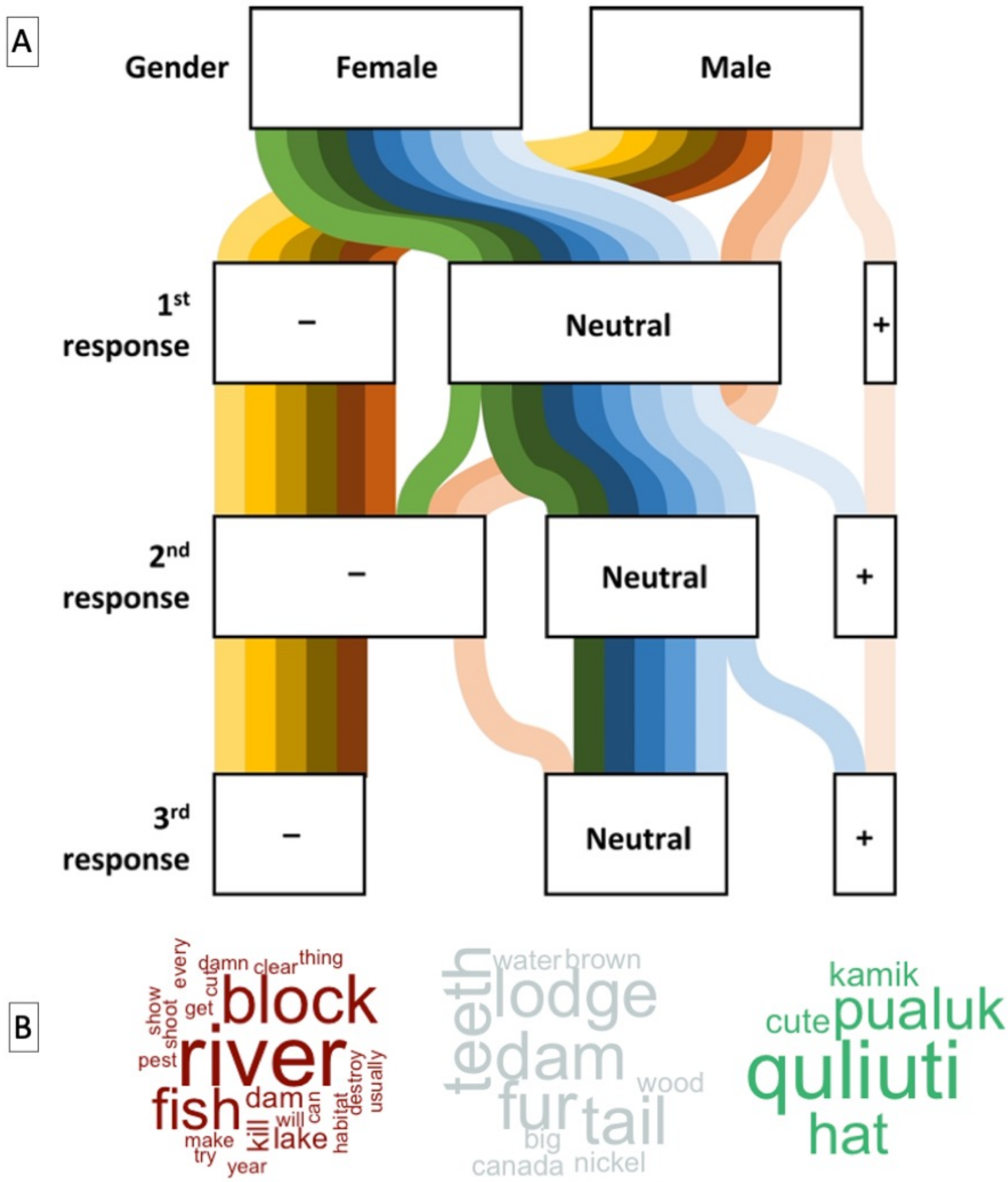

Figure 5. Responses to the question "When you think of beavers, what are the first 3 words that you think of?". a) Sankey plot of respondents' (indicated by colour) answers categorized by gender as positive (+), neutral (n), or negative (-) for each of the three responses. b) Word cloud of positive (green), neutral (grey), and negative (red) responses, in both English and Inuktitut.

In Tasiujaq, most community members who filled in the questionnaire had not ever tried beaver meat, and only 13% of respondents said that they would consider making beaver meat a regular part of their diet (Figure 6). The follow up question to "would you ever consider making [beaver meat] a part of your normal diet?" was "why?", and to this, community members listed reasons such as "I rather eat what I know" and "because I never ate it when I was growing up".

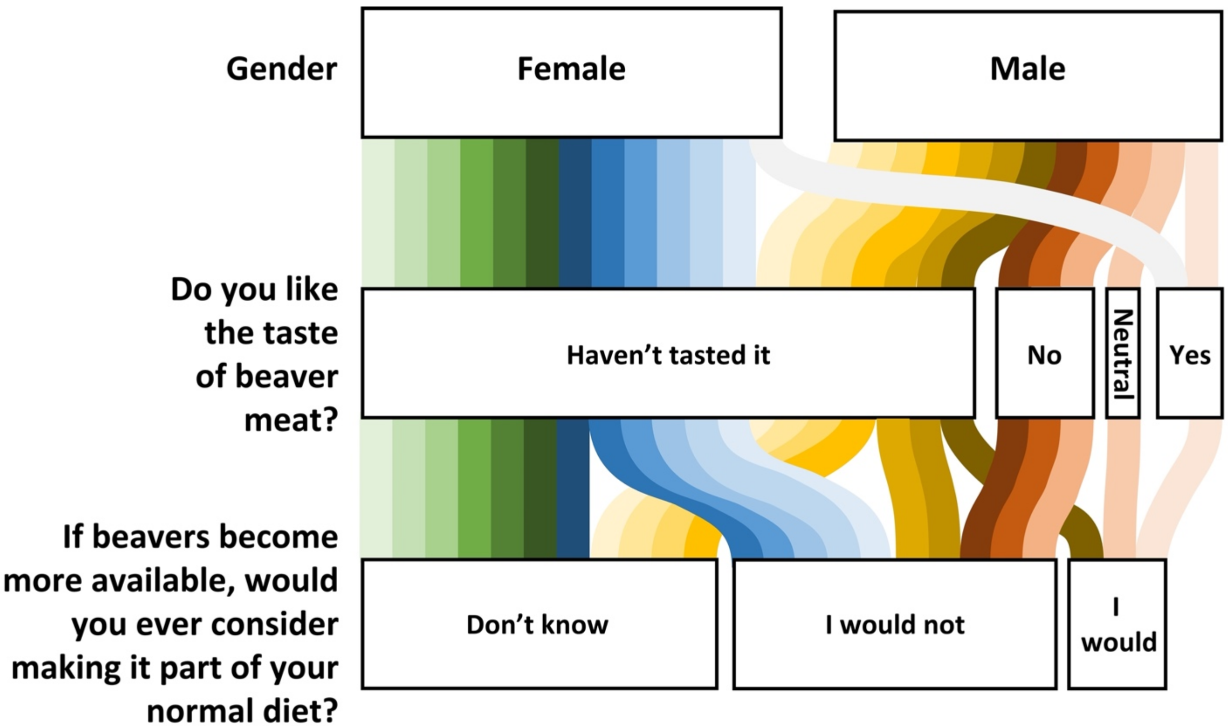

Figure 6. Responses to the questions "Do you like the taste of beaver meat?" and "If beavers become more available, would you ever consider making it part of your normal diet?" represented through a Sankey plot. Individual respondents (indicated by colour) are categorized by gender.

The beaver questionnaire in Tasiujaq asked respondents to rate their general knowledge of beavers from 1 to 10, and 38% of respondents rated their knowledge of beavers as 1 (no knowledge of beavers), while 14% rated their knowledge of beavers as 8 or more (highly familiar with beavers and their activities).

Discussion

In Nunavik, a primary concern related to beaver range expansion is the interaction between beavers and Arctic char, especially concerning the impact of beaver dams on char's upriver migration during the fall. Arctic char interviews conducted with 57 respondents from six Nunavik communities and beaver questionnaires completed by 26 residents of the community of Tasiujaq confirmed that the impacts of beaver dams on Arctic char migration are a primary concern of Nunavimmiut harvesters and wildlife management organizations. Interviews indicated that the beavers were first observed in Nunavik in the late 1950s to 1960s and have expanded northward since, along the Hudson coast and Ungava Bay. Beaver range expansion into the Arctic has been mainly attributed to climate change and increasing shrub cover (Tape et al., 2018). While this hypothesis was supported by some Nunavik knowledge holders during interviews, respondents suggested that there may be additional influences contributing to beaver range expansion in Nunavik, including reduced harvest pressure from First Nation trappers following settlement into villages and reduced habitat quality in southern regions associated with hydroelectric developments.

Here we present a mixed method approach for designing wildlife surveys at range edges that combines the wildlife observations of local knowledge holders with additional systematic and random sampling of areas beyond local observations. In the current study, inclusion of locally identified beaver sites in the survey design greatly increased species detection within a vast region characterized by low and aggregated population abundance. The survey was able to confirm which locally observed colonies were still active at the time of the survey and verify areas with similar habitat conditions that may be less accessible to harvesters. In this manner, the survey provided spatially-extensive documentation of active and inactive beaver sign at a single point in time, while local knowledge extended observations over longer time frames required to understand transient events. Observations from Inuit hunters and knowledge holders evidenced the pattern of beavers moving northwards, from the limits of the boreal forest into the treeless landscape of Nunavik tundra. Importantly, these observations include the occasional presence of beavers far from the range edge, where individuals are seen swimming but dams and lodges have not been constructed, consistent with dispersal and exploration but not successful population establishment. Related to this, it is noteworthy that among locally identified transects, the lowest proportions of observed beaver activity tended to coincide with the most northerly transects and the highest proportions of observed activity with more southern transects. In other words, at the range margins it was more common for local observations of beaver presence to not be documented during a snapshot-in-time wildlife survey, highlighting the importance of local knowledge in documenting transient events. Although beaver may be present only occasionally in these regions, should climate change increase suitability of those regions, specifically through shrubification (Duchesne et al., 2018; Myers-Smith et al., 2011), it is possible that beavers may be able to settle more permanently (Gallant et al., 2004; Tape et al., 2018). In addition, hunters have observed beavers swimming along the shoreline in the bay. Although beaver are almost always associated with freshwater systems, they have been observed swimming in marine waters and establishing in tidal marshes in other coastal regions (Anderson et al., 2009; Hood, 2012; Pasternack et al., 2000). In Yukon, beavers are speculated to have colonized the Beaufort Coastal Plain using the Beaufort sea as a dispersal corridor, which circumvents the terrestrial and freshwater barrier created by the south-north continental divide (Jung et al., 2017). Thus, while beaver establishment in saltwater habitats may be uncommon, marine connectivity among freshwater systems may facilitate population dispersal and establishment at range edges. In the case of western Ungava, the bay may provide a travel corridor between otherwise isolated freshwater drainages, such as between the Leaf River drainage where beavers are established and the Payne River drainage far to the North where beaver have occasionally been observed. As shown in the current study, Inuit knowledge and community-based monitoring are more likely to detect these rare and ephemeral dispersal events than occasional systematic surveys.

The negative impacts of beavers most often observed and communicated by Nunavimmiut were beaver dams creating a barrier during Arctic char migration. In follow up conversations, concerns were also raised regarding the impacts of beavers on Arctic char spawning, other fish species, and drinking water. When asked to describe beavers in 3 words, most of the terms chosen by Tasiujarmiut were neutral or negative. Positive terms were usually associated with clothing and sewing, such as the use of beaver fur in the trim of mitts (quliuti) or in boots (kamiik). Despite their usefulness in clothing, beavers were generally seen as negatively impacting food security because of their impact on Arctic char.

Many Nunavimmiut who raised concerns about the northward expansion of beavers had ideas for how to adapt to or manage beaver impacts. Recommendations included further research on beaver distribution and impacts in Nunavik and financial incentives to encourage beaver trapping. Suggestions also focused on improving Inuit knowledge of beaver trapping and preparation through knowledge sharing workshops with more experienced Cree trappers. The possibility of integrating beaver into the subsistence system was dismissed by many who felt that the taste was not appreciated by Inuit; they suggested instead that the meat be shared with the Cree. Amongst respondents in Tasiujaq, most suggested that they were hesitant to make beavers a regular part of their diet because it was not a traditional country food. In informal discussions, however, some who were unsure about integrating beaver meat into their diet expressed an openness to the possibility of reconsidering their opinion, particularly if they could improve their cooking techniques through exchanging beaver preparation tips and recipes with Cree. In Kuujjuaq, a beaver working group has been formed between the Kuujjuaq Hunting Fishing Trapping Association, Nunavik Research Centre, and Landholding Corporation, with a goal of more effective beaver management and research planning. Conversations, working groups, and research related to beaver management are increasing across Nunavik as communities recognize the potential impacts of this ecosystem engineer on local food and habitats.

Conclusion

In this article, we examine the historical and contemporary distribution of beavers in Nunavik, local perceptions of beaver and their impacts on other Arctic species and landscapes. The findings reveal that Nunavimmiut have observed recent northward expansion of beaver and concern over their impacts on char and water quality. Rapid range shift, ecological engineering, and novel species interactions make beaver populations a real concern for Inuit communities, and understanding the spatio-temporal dynamics of their expansion is imperative for effective management. Continued and improved monitoring of beaver presence in the coming decade, through tools such as remote sensing and local monitoring, will be vital to equip Nunavimmiut with the knowledge needed for effective management. Adaptation policy and action that is led by Inuit, informed by Inuit knowledge, and supported by research is critical in order to establish long term solutions to address the northward expansion of boreal species into Arctic regions.

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CONNECTING STATEMENT

The previous chapter integrated Inuit and aerial survey knowledge of the range expansion and impact of beavers in Nunavik through multiple methods including interviews, a helicopter survey, and questionnaires. The results confirmed the importance of this research topic to Nunavimmiut in general as well as to Tasiujarmiut specifically, documented Inuit knowledge and observations of beaver presence over time, outlined main concerns regarding beaver impacts, assessed the feasibility of several adaptation options, and allowed for management recommendations to be summarized. Ongoing monitoring of beaver distributions is necessary to inform and direct management action, but monitoring can be costly and logistically challenging across the vast Nunavik landscape. Monitoring activities and surveys can be better concentrated if informed by region-specific habitat use analyses, which elucidate important environmental factors that may determine suitability of a region for beaver. Local observations and helicopter survey data are included in both chapters to maintain the representation of Inuit and scientific knowledge throughout the thesis. Chapter 1 offers a timeline of beaver occurrence and an integrative and holistic understanding of beaver range expansion and its socio-ecological impacts. In Chapter 2, local observations and helicopter data are combined to estimate regional variation in beaver colony density and to model beaver habitat selection. Although Chapter 2 emphasizes quantitative ecological analysis, the survey design and analysis incorporate Inuit knowledge, interpretation, and management implications. Accordingly, these two manuscript-based thesis chapters are complementary, intended as stand-alone but sequential publications oriented around a foundation of Inuit knowledge and concerns.

CHAPTER 2: BEAVER (*CASTOR CANADENSIS*) DISTRIBUTION AND HABITAT USE IN WESTERN UNGAVA, NUNAVIK

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Abstract

Expansion of boreal species into Arctic regions, and their impacts on local biodiversity and Inuit subsistence, is a key knowledge priority in arctic science and for northern communities. Beavers (*Castor canadensis*) are ecosystem engineers that re-configure aquatic and terrestrial habitats in forested biomes and, following recent poleward expansions, beyond the treeline into the Arctic. Here we combine Inuit knowledge, helicopter surveys, and habitat classification to document the distribution and habitat use of beaver in western Ungava, Nunavik Canada. Inuit knowledge from the communities of Tasiujaq and Aupaluk contributed 24 local knowledge localities known to be inhabited recently or in the past by beavers. A helicopter survey of beaver lodges, caches, and dams along waterways consisted of 69 transects, each 10-15 km in length, including 15 transects with locally identified beaver locations and 54 systematic transects where beaver presence or absence was unknown. Across the entire 867 km survey, observed beaver sign included 46 lodges, 22 food caches, 33 dams, and 8 partial dams situated within 5 of 15 (33%) locally identified transects and 8 of 54 (15%) systematic transects. Active colony density averaged 0.06 colonies/km for locally identified transects (maximum = 0.5 colonies/km), 0.02 colonies/km for systematic transects (maximum = 0.3 colonies/km), and 0.03 colonies/km for the study region as a whole. When comparing transects with and without beaver presence, habitat selection analysis focused on the landscape scale indicated beaver selection of water body type (streams > rivers > small lakes > large lakes), conifer presence, low elevation, and low latitude, whereas selection analysis focused on a local scale (within transects) indicated a primary importance of water body type (stream > river ≈ small lake > large lake). These results provide a mixed methods quantification of beaver distribution, abundance, and habitat selection above and below treeline in the western Ungava region of Nunavik, including the low latitude, low elevation, stream, river, and small lake watercourses where beaver presence is currently concentrated. This information can be used to track further expansion of beaver in Nunavik, model current and projected future habitat suitability, and prioritize locations for assessment and potential control of beaver impacts on Arctic ecosystems and the Inuit country food system.

Introduction

Beavers are ecosystem engineers that significantly modify their environment through their damming, cutting, and building activities (Naiman et al., 1988; Collen & Gibson, 2001; Kemp et al., 2012; Macfarlane et al., 2017). The construction activities of beavers provide them with safety from predators, a shelter for overwintering, and access to their preferred food (Gallant et al., 2004; Müller-Schwarze, 2011; Salandre et al., 2017; Mumma et al., 2018). Beavers engineer structures including dams, lodges, bank burrows, and canals, which can restructure plant communities, transform streams into wetlands, and modify biodiversity (Naiman et al., 1988; Pollock et al., 2003; Brazier et al., 2021). These rodents are valued for the ecosystem services that they provide across most of their spatial distribution; however, their recent expansion into the Arctic has brought up concerns regarding the effect of their activities on permafrost, native biodiversity, and the movement of Arctic fish species (Tape et al., 2018; Jones et al., 2020; Neelin, 2021). This spatial shift may threaten the success of native species and Indigenous harvest, therefore many harvesters and management bodies are invested in understanding and regulating the problem. (Brubaker, Bell et al., 2011; Brubaker, Berner et al., 2011; Meredith et al., 2019; Jones et al., 2020; Neelin, 2021).

In order to effectively manage a new and unfamiliar species, it is important to understand its distribution. In a region as vast and sparsely inhabited as Inuit Nunangat, the Inuit-occupied region of northern Canada, it may be difficult to localize beavers despite the recognizable indicators of their presence. In Nunavik, which is the Inuit region that lies north of the 55^{th} parallel in Quebec, communities are fly-in only and road networks around villages do not extend very far. Harvesters hunt and fish by travelling by boat, skidoo, or all-terrain vehicle (ATV), primarily along river systems, ocean routes, and trails near the village (Chanteloup et al., 2018; Ready & Collings, 2020). Observations of beaver signs by Inuit hunters are invaluable for monitoring beaver expansion, but there are still many regions that are rarely travelled, and thus some beaver colonization routes may be overlooked (Neelin, 2021). In order to fill those knowledge gaps and improve understanding of beaver distribution and expansion, researchers may conduct aerial surveys. When planning beaver surveys to inform management decisions, an understanding of habitat selection and preferred colonization sites is important in order to prioritize and concentrate efforts, particularly because monitoring in the Arctic is costly and logistically challenging (Christensen et al., 2020). Elucidating the characteristics of beaver building activities and environmental variables that might influence beaver land use in Nunavik may help project planners evaluate which water bodies are capable of supporting present and future colonization. This information can be invaluable for researchers and management bodies who wish to comprehend and manage this unfamiliar species.

Research on habitat selection by beavers has found that beaver occurrence is driven mainly by habitat quality, including available riparian and aquatic vegetation, consistent water supply, water body size, stream gradient, and ruggedness, among other geomorphological and vegetative characteristics (Smeraldo et al., 2017; Touihri et al., 2018; Mumma et al., 2018; Hood, 2020; Ritter et al., 2020). While they are well known for their intake of woody vegetation, which consists mainly of deciduous trees and shrubs and is important for overwintering survival, herbaceous plants, such as grasses, forbs, and aquatic vegetation, are a significant part of beaver diets in many environments (Jenkins, 1979; Busher, 1996; Parker et al., 2007; Milligan & Humphries, 2010). Beavers are based out of a central location, the majority of foraging activities take place in the 50 m buffer around water bodies, and they transport food not immediately consumed back to the same location (Stoffyn-Egli & Willison, 2011). Thus, they are central-place foragers, which limits their dispersion into new areas and may complicate analysis of habitat selection (McGinley & Whitham, 1985; Basey et al., 1988; Basey & Jenkins, 1995; Raffel et al., 2009; Hood, 2020). Additionally, habitat selection by beavers in one study usually cannot be directly applied to another area, as important habitat variables may vary depending on spatiotemporal scale and ecological setting (St-Pierre et al., 2017; Touihri et al., 2018; Hood, 2020). Important habitat variables during beaver expansion and initial colonization may differ from those in areas where beaver populations are at high densities (Pinto et al., 2009). As such, studies on beaver habitat selection at the core of their range cannot be extrapolated to their northern limits, especially since the long, cold winter and lack of deciduous trees constrain their survival (Aleksiuk & Cowan, 1969; Jarema, 2006). Habitat selection studies done in Quebec have been restricted to areas below Nunavik, with the exception of Jarema et al. (2006), so very little is known about what habitat factors may influence beaver occurrence in this region. Around Koksoak River, near Kuujjuaq, Nunavik, beavers selected for areas with coniferous tree cover and small lakes, but avoided rivers (Jarema, 2006). In that study, aquatic vegetation was absent and satellite imagery did not have a fine enough resolution for shrub characterization, although those are two large contributions to beaver diets and survival of beavers in the northern edge of their range (Novakowski, 1965; Aleksiuk & Cowan ,1969; Milligan & Humphries, 2010). North of Kuujjuaq, particularly above the treeline, we hypothesize that deciduous shrub cover is the main limiting factor for the survival of beavers and will be strongly selected for. We also expect that beavers will be more abundant in areas with conifer presence, low elevation, areas dominated by streams, low riparian slope, and low proportion of non-woody vegetation cover (Supplementary Table S1). Finally, we expect that for beaver colonies present along watercourses (streams and rivers), a low gradient (approximately 2-4%) and large stream width will be important predictors of beaver presence (Touihri et al., 2018). This research aims to characterize the features, density, and habitat selection of beaver colonies along western Ungava to inform future research and management practices.

Methods

Study Area

Nunavik is a region of 14 remote Inuit communities that is situated in northern Quebec and is bordered by Ungava Bay, Hudson Straight, and Hudson Coast. The area surrounding two communities (Tasiujaq and Aupaluk) along the western coast of Ungava Bay was selected as the study area due to frequent observations of beavers and beaver sign by community members, especially from the community of Tasiujaq, combined with community interest in documenting beaver presence and impacts on native species, including Arctic char. The community of Tasiujaq is located near treeline while Aupaluk is situated in treeless, tundra landscape.

Community-based Participatory Research

This research project was motivated by a report summarizing knowledge from 66 Elders, hunters, and fishermen from 10 Nunavik communities regarding concerns about Arctic char populations and management recommendations to protect Inuit access to this key food species (Neelin, 2021). Respondents in six of ten communities mentioned beaver observations and concerns related to their interactions with Arctic char migration and recommended that research examine the present distribution of beaver and variables promoting their range expansion. This project grew from those recommendations to address these questions using a participatory research approach that included Makivik Corporation, the Regional Nunavimmi Umajulirijiit Katujiqatigiininga (RNUK; the Hunting, Fishing, and Trapping Association), and the Tasiujaq Nanuapiit Board (Hall, 1992; Drawson et al., 2017). These Nunavik representative groups directed research goals, guided the project, contributed local knowledge, assisted with surveys and site visits, and provided feedback on results and interpretation. Additional sources of Inuit knowledge included in this study include content presented in Neelin (2021).

Inuit Knowledge

Arctic char interviews were conducted with Nunavik knowledge holders, which included harvesters, pilots, and wildlife managers, in ten Nunavik communities (Neelin 2021). The report aimed to synthesize concerns about the impact of climate change on Arctic char and the subject of beavers was discussed with six of the ten communities in relation to this theme. Local knowledge holders from four communities (Kangiqsualujjuaq, Kuujjuaq, Tasiujaq, and Aupaluk) identified areas where they had directly observed beaver signs (sightings of beaver dams, lodges, or the animal itself) on a 1/50 000 Canada National Topographic System map during Arctic char interviews. These areas, which may have been inhabited by beavers recently or in the past, are referred to as locally identified beaver sites. Interviews were done by MNN under the supervision and guidance of Makivik Corporation and respecting their ethical guidelines. Use of data from these interviews (Neelin, 2021) was approved by the McGill University Research Ethics Board Office (REB File #19-10-042). All participants provided written consent for their participation.

Helicopter Survey

A total of 866.6 km of waterways (e.g. lake shores, rivers, streams) were surveyed for beaver sign, including 69 survey transects, each 10-15 km in length. Total transect length was equally distributed within 6 survey blocks (136-146 km per block), two focused on locally identified regions of known beaver presence in proximity to Tasiujaq and Aupaluk (locally identified survey blocks) and four situated adjacent to and scaled to be equal in total area to locally identified blocks (systematic survey blocks). Within locally identified survey blocks, transects were situated along waterways locally identified to be characterized by beaver presence (locally identified transects) as well as additional waterways within the block where beaver presence or absence had not been communicated (systematic transects). Thus, locally identified survey blocks included both locally identified and systematic transects, whereas systematic survey blocks consisted of only systematic transects. Within locally identified survey blocks, all routes that intersected with locally identified beaver signs were selected as locally identified transects, and then additional routes along waterways were randomly selected to serve as systematic transects until the total transect lengths within a block reached 136 km to 146 km. The final transects selected for the helicopter survey are shown in Figure 1a. Additional local knowledge and transect selection methodology is described in Neelin et al. (2021)

The helicopter survey was conducted during the autumn (31 September 2019 and 1 October 2019) in order to allow for identification of food caches (Hay, 1958). The helicopter followed the planned transects as closely as possible at a speed of approximately 100 km/h and remained approximately 70 m above ground level, flying along the left bank of rivers and lakes when the water body widened unless the transect directly crossed the lake to continue following the water system. The pilot and observer sat in the front of the helicopter, while the note-taker/navigator sat on the rear left seat. Any time that a beaver sign was observed, the helicopter circled closer so that the observer and notetaker could investigate the site, check for other beaver signs near the one observed, take photos, and record the waypoint. Any deviations from the transect to investigate beaver sites were removed from the transect length for the beaver density analysis.

Active versus inactive sites were distinguished by fresh food caches or by the presence of newly added mud and branches in the lodges and dams. Colonies were distinguished from each other by the presence of a single food cache per colony (Bradt, 1938; Fuller & Markl, 1987), or, in the case of 5 active lodges where no food cache was found, by being > 1 km away from any other active beaver sign.

To compare areas of beaver presence to areas of beaver absence, the 69 survey transects, each 10-15 km in length, were subdivided into 500 m long segments (i.e., 20-30 segments per transect). If beaver sign was observed within a segment, it was classified as a beaver present segment (with sign qualified as either active or inactive). If beaver sign was not observed within a segment, it was classified as a beaver absent segment. Categorization of the presence of beaver signs (lodges, food caches, dams, or partial dams) in each segment encompassed both segments that are actively occupied by beavers and those that were occupied in the past but are now abandoned, since successful beaver colonization events in this marginal habitat would imply at least tolerable environmental conditions.

Predictive variables of beaver presence and absence

Candidate variables included for the habitat selection analysis included 1) percent shrub cover in the 50m buffer around water bodies, 2) presence or absence of conifers in the 50m buffer around water bodies, 3) percent non-woody (no conifers or shrub cover) in the 50m buffer around water bodies, 4) water body type (streams, rivers, small lakes, and large lakes), 5) latitude (in decimal degrees, WGS84 reference coordinate system) at the transect mid-point, 6) average elevation in the 50m buffer around water bodies, and 7) average ruggedness in the 50m buffer around water bodies, used as a proxy for bank slope or steepness. These environmental variables were assessed from publicly available raster layers created by the Canadian and Quebec government based on satellite imagery (Supplementary Table S1). Environmental variables within 50 m of waterway shorelines ("shoreline buffer") were considered for analysis, since that is the area where beaver activity is concentrated (Stoffyn-Egli & Willison 2011). The 500 m segments created from the flown helicopter transects (see above), were buffered 400 m , so that each "segment buffer" was 800 m wide x 500 m long. Candidate variables, including vegetation cover, elevation, and ruggedness, were considered in the analysis only for those areas where the shoreline buffer intersected with the segment buffer, so that environmental variables opposing shorelines on lakes wider than 800 m were not included and shoreline buffers were associated with a unique segment. Conifer presence and absence was treated as binary because segments tended to have either no conifer present or substantial conifer present. For the fourth variable, water body type was categorized as stream, river, small lake (less than 2 km^2), or large lake (2 km^2 or larger). The water body type for each segment was the dominant class that was present, based on the percentage of each water class along the shore to avoid overrepresenting wide water bodies. Latitude was extracted for the midpoint of each segment, while mean ruggedness and elevation in the 50m buffer around the water bodies were calculated from a digital elevation model (DEM) using QGIS Raster Terrain Analysis and Raster Layer Statistics (Supplementary Table S1).

Two additional habitat variables analyzed only for streams and rivers were gradient (% slope) and average width (m). Watercourse gradient was calculated using the elevations from the DEM at the start and end of the segment, with gradient calculated as vertical drop (m) divided by distance (m). Watercourse width was calculated for each segment using the area of the CanVec watercourse vectors within one segment (m^2) divided by the length of the centre line of that watercourse (m; Supplementary Table S1).

Habitat selection analyses

We considered habitat selection at the scale of the 11028 km^2 study region, which we refer to as a landscape scale, and at the scale of 500m segments within 10-15km transects, which we refer to as a local scale. For landscape scale analysis, segments with observed beaver sign are compared to segments across the entirety of the survey area where no beaver sign was observed, whereas for local scale analysis, segments with observed beaver sign are compared to neighboring segments along the same watercourse and within the same transect, where no beaver sign was observed and for which no part of the segment is within 1 km of the observed beaver sign. Given transect segments were 500 m in length, the no beaver sign observed segments used in comparisons were typically not neighboring segments but rather were two or three segments away from beaver sign observed segments. If no non-beaver segments were available along the same transect (which occurred in two cases), the closest non-beaver segment was selected from a neighbouring transect.

We considered non-metric multidimensional scaling (NMDS ; Kruskal, 1978) and regression models, including both generalized linear models, GLMs, and generalized linear mixed models, GLMMs (Bolker et al., 2009; Thiele & Markussen 2012) as analytical approaches to assess relationships between beaver observations and habitat variables. In all cases, bivariate correlation tests and univariate analyses were used as a preliminary step to identify uncorrelated predictor variables and explore one-to-one associations between habitat characteristics and beaver observations.

For univariate analyses at a landscape scale, the data were balanced by randomly selecting the same number of segments with beaver observations and segments without beaver observations, referred to as “down-sampling” (Visa & Ralescu, 2005). For local scale analysis, neighbouring segments with beaver observations and segments without beaver observations were selected, as described above. For continuous habitat variables with a normal distribution (normality verified using a histogram and a normal quantile-quantile plot), an unpaired t-test assuming unequal variances (Welch t-test) was used to compare the means. For categorical variables and data that could not be transformed into a parametric distribution, an unpaired (two-sample) Wilcoxon test (Noether, 1992) was used to test differences in distributions of segments with beaver observations and segments without beaver observations, using the rstatix function wilcox_test in R version 4.0.2 (Kassambara, 2020; R Core Team, 2021).

Non-metric multidimensional scaling (NMDS) using Bray-Curtis dissimilarity explored using the function metaMDS from the vegan package (Oksanen et al., 2013). The number of dimensions were selected such that stress was minimized to a level below 0.2 (Clarke, 1993). A Shepard diagram was used to ensure the goodness of fit with the selected number of dimensions (Tenreiro Machad et al., 2015). Convex hulls represented the occurrence of segments with beaver observations and segments without beaver observations to facilitate visual analysis.

To model the presence of beaver sign as a function of the environmental covariates at the landscape scale, a binomial generalized linear mixed model with a logistic link function was used. Model goodness of fit was evaluated on the global (most complex) model using residual diagnostic tests with the DHARMa R package (Hartig, 2017). Percent shrub cover, non-woody vegetation cover, and ruggedness were removed because they caused non-convergence of the regression model. *Dominant water body type* (categorical with four levels), *presence of conifers* (categorical with two levels), *mean elevation* (continuous) and *latitude* (continuous) were the fixed covariates of the global model, and transect was used as a random intercept. Candidate models were generated and compared using the dredge function of the MuMIn R package (Bartón, 2015). This approach is to be distinguished from the generally defined data dredging approach (Burnham & Anderson 2002), which considers many variables with little reasoning or scientific basis and can lead to overfit models with spurious results. In this study, this particular multimodel inference approach was used because the limited number of environmental variables included were each ecologically meaningful, selected with an a priori motivation, and could have the potential to contribute to the model in varying ways. Thus, the dredge function was used to explore the many possible additive effects of a limited set of meaningful candidate environmental variables, similar to a manually created list of possible combinations of candidate models. Segments were not subset for this landscape scale analysis, since GLMMs can effectively process hierarchical spatial data and down-sampling has the potential to remove useful data (Visa & Ralescu 2005; Durán Pacheco et al., 2009). Transect IDs were retained as a random effect in the model to account for potential non-independence from beaver dispersion along waterways within the same transect. The top six models resulting from the dredging (the "final candidate set") were compared using the Akaike's information criterion corrected for small sample size (AICc) due to the small sample of segments with beaver observations and to account for the random effect (Burnham & Anderson, 2002; Vaida & Blanchard, 2005; Brewer et al., 2016). Model goodness of fit was evaluated on the global (most complex) model using residual diagnostic tests with the DHARMa R package (Hartig, 2017) and subsequently on the top ranked model by calculating marginal and conditional R^2 using the MuMIn package (Barton, 2015), which represent the variance of the fixed effects only and of the whole model, respectively (Nakagawa & Schielzeth 2013). The AICcmodavg package in R (Mazerolle, 2020) was used to compute model-averaged parameter estimates of the final candidate set models that fell within a ΔAIC_c of 6.00 (Richards, 2005; Harrison et al., 2018). For a local analysis, the subset of neighbouring segments with observed beaver sign and no observed beaver sign were analyzed using GLMs in a similar way, but without the random effect of transect: a binomial generalized linear model with a logistic link function was used, model goodness of fit was tested on the global model, candidate models were compared using the dredging approach, the candidate set models were compared using AICc, model goodness of fit was tested on the top ranked models, and parameters were evaluated using model averaging of models in the final candidate set that fell within a ΔAIC_c of 6. McFaddens R^2 (Pseudo-R^2) of the GLM was calculated using the LogRegR2 function in the descr R package (Aquino, 2021). The covariates of the global model at the local scale were *dominant water body type* (categorical with four levels), *percent shrub cover* (continuous), *presence of conifers* (categorical with two levels), *ruggedness* (continuous), *mean elevation* (continuous) and *latitude* (continuous).

Beaver site visits

Beaver site visits allowed for closer inspection and measurement of beaver dams, lodges, and food caches, as well local assessment of the terrestrial and aquatic vegetation present at the site. Site visits included helicopter landings during the survey as well as opportunistic trips to sites when access was feasible by skidoo, freighter canoe, small canoe, and foot. When access allowed, dams were measured from beginning to end, including the sections that were constructed on land. Site visits included the inspection of 13 dams and 25 lodges (Supplementary Table S3).

Results

Beaver sign observations and colony density

A helicopter survey along a total of 8,677 km of western Ungava waterways (stream, rivers, and lakes), yielded observation of 103 active and inactive beaver signs; 6 additional signs were observed while crossing between transects (Figure 1). Beaver sign observations included 46 lodges, 22 food caches, 33 dams, and 8 partial dams, and were surrounded by varied vegetation cover, including low shrubs, high shrubs, coniferous trees, and a mix of woody vegetation (Figure 2). A variety of dams were observed, including long dams (Figure 2a, 2c), high dams (Figure 2b), and abandoned dams that had burst (not shown). Most observed lodges were built on land, either into banks (Figure 2d) or on flat shorelines (Figure 2e); free-standing lodges surrounded by water (Figure 2f) were uncommon.

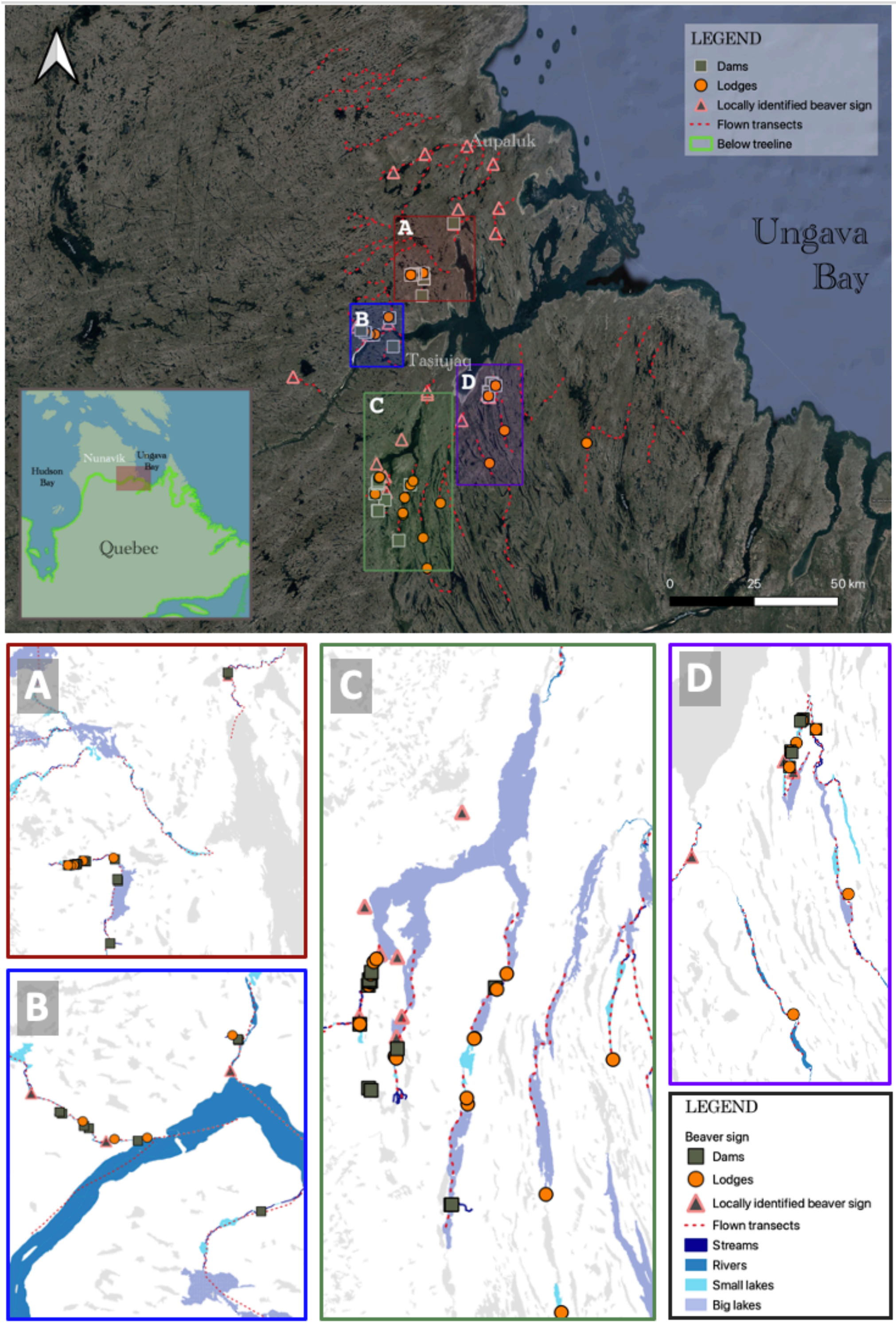

Figure 1. Locations of survey transects (red dashed lines), and observed beaver sign, including lodges (orange circles), dams (grey squares; including partial, abandoned dams), and locations of locally identified beaver sign (red-grey triangles). Letter insets (a-d) highlight subsurvey areas where most beaver sign was observed, at a scale where flown transects (red dashed lines) and

water body type (see legend) associated with most beaver observations are visible. Letter insets represent beaver sign in the areas near: a) Ammaluttuq and Mannic lakes, b) Leaf River, c) Finger Lake, and d) Tasiujatuqaq.

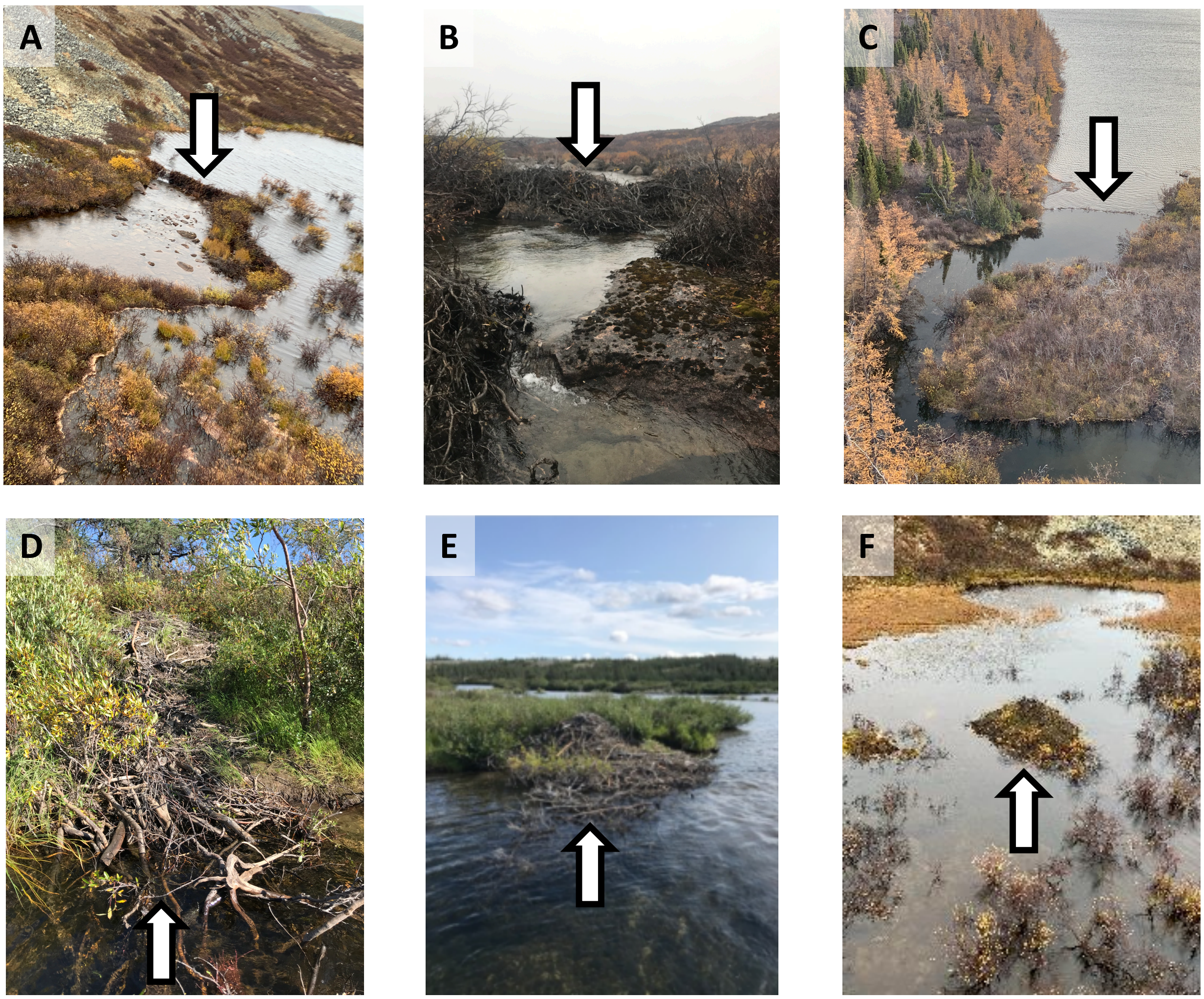

Figure 2. Photos of beaver dams (a-c) and lodges (d-f) observed in the western Ungava region of Nunavik, Quebec, Canada. Three general lodge types were observed, with bank lodges built in high shorelines (d) most common, low shore lodges built adjacent to flat shorelines (e) second most common, and free-standing lodges surrounded by water (f) least common.

Beaver sign was observed within 5 of 15 (33%) locally identified transects and 8 of 54 (15%) systematic transects (Figure 3). Active colony density averaged 0.06 colonies/km for locally identified transects (maximum = 0.5 colonies/km), 0.02 colonies/km for systematic transects (maximum = 0.3 colonies/km), and 0.03 colonies/km for the study region as a whole. Maximum colony density was 0.49 active colonies/km observed on a locally identified transect. No active colonies were observed on 56 of 69 surveyed transects.

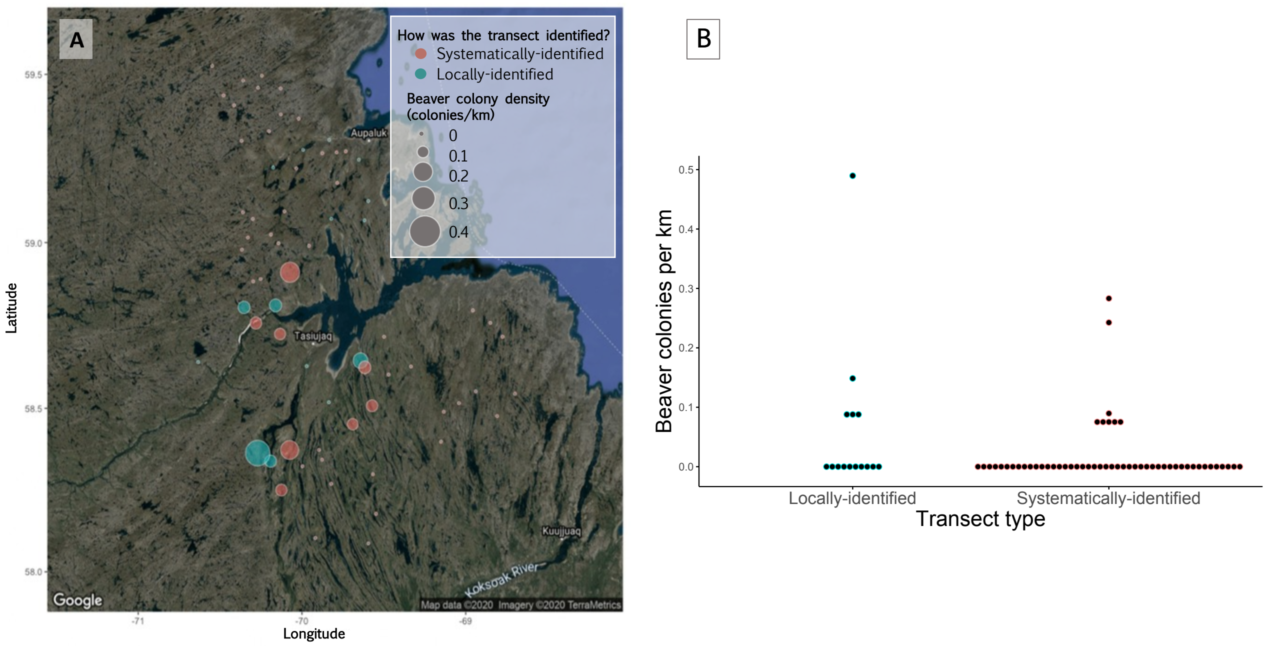

Figure 3. Map (a) and dot plot (b) of colony density within locally identified (blue) and systematically identified (red) transects.

Habitat Selection

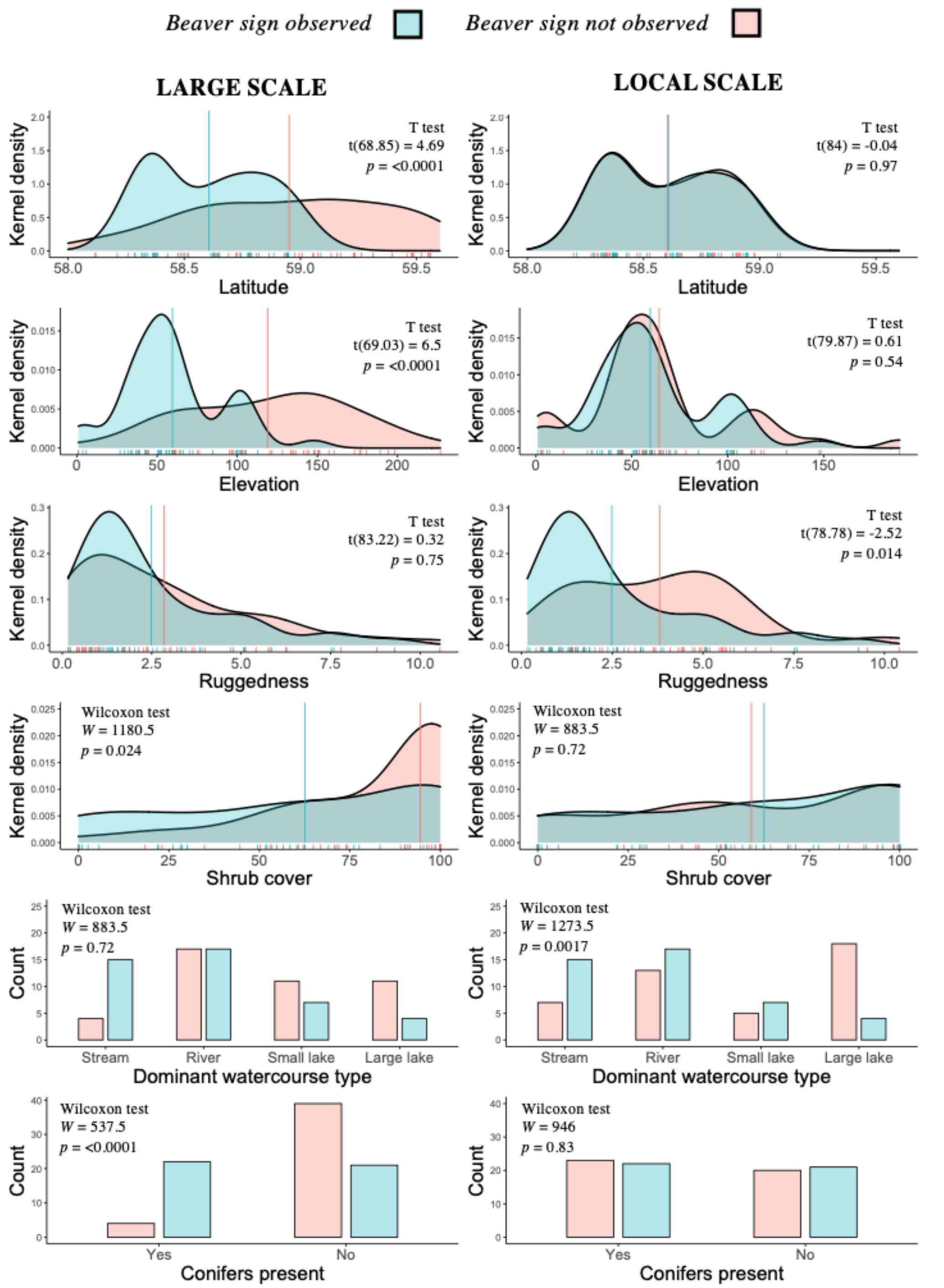

Figure 4. Kernel density estimate of the distributions of continuous candidate variables and barplots of the counts of discrete candidate variables to compare differences between segments with beaver observations and segments without beaver observations at a landscape scale

(comparing segments with beaver observations to randomly selected segments without beaver observations) and local scale (comparing segments with beaver observations to neighbouring segments without beaver observations), with associated rug plots below. Included above each plot are the results from the univariate test: the unpaired t-test assuming unequal variances for normally distributed data and the unpaired (two-sample) Wilcoxon test for non-normalized data (n=86 in all cases). Vertical lines represent the mean value in cases of the unpaired t-test and median values in cases of the unpaired (two-sample) Wilcoxon test.

Predictor variables that are strongly informative for detecting beaver presence differ between the landscape scale and local scale in all cases except for dominant water body type (Figure 4). At both scales, streams are dominant in more segments with beaver observations than in segments without beaver observations. Segments with beaver presence were most often dominated by streams (34.9%) or rivers (39.5%), and uncommonly dominated by small lakes (16.3 %) or large lakes (9.3 %). In comparison, streams are the dominant water body type in only 9.3% of segments with no beaver observations at the landscape scale. The differences between dominant water body types are only weakly informative at the landscape scale but become strongly informative at the local scale. When considering the other variables at the landscape scale, ruggedness in the 50 m buffer around water bodies does not seem to differ greatly between segments with beaver observations and segments without beaver observations while elevation, latitude, conifer presence, and shrub cover do. At this scale, beavers are present in more segments that are at a lower latitude, lower elevation, lower shrub cover, and where conifers are present. Although these differences are informative at the landscape scale, they disappear or weaken at the local scale. The opposite is true for ruggedness; the small tendency towards lower ruggedness at segments with beaver presence at the landscape scale is amplified at the local scale.

Focusing only on segments dominated by streams or rivers, median watercourse width for segments with observations of beavers is 25.89 m, while median watercourse width for segments without observations of beavers is 43.73 m (Supplementary Fig. S1). One of the watercourses with beaver signs present is an outlier: a lodge built on the shore of a wide (274 m) river. No dams were observed at that site. Stream gradients of these watercourses were very small, with a median of 0.46% for segments with beaver presence and a median of 0.37% for segments with no observed beaver sign; this difference was not informative (p = 0.53). The maximum gradient for all segments included in this comparison was 6.11%.

NMDS exploration of interactions between beaver presence and multiple environmental variables indicated that three dimensions reduced the stress to an acceptable level of 0.129 at the landscape scale and 0.105 at the local scale (goodness of fit was confirmed through a Shepard diagram at both scales). However, the resulting NMDS plots revealed high overlap between segments with beaver observations and segments without beaver observations, indicating low dissimilarity (Supplementary Fig. S2). Although dissimilarity is small, the distinctions that are present are mainly driven by dominant water body type. In the landscape scale analysis, the highest environmental variable loadings were those of rivers (-0.60) and small lakes (0.63) in the first axis, and large lakes (-0.85) and presence of conifers (-0.63) in the second axis. Similarly, local-scale analysis revealed that axis 1 was influenced mainly by large lakes (0.84), axis 2 by non-woody vegetation (0.87), and axis 3 by small lakes (-0.69).

In cases where ordination is unable to properly describe patterns in the data, it may be an indication that there are predictors missing from the data or that there is minimal correlation between variables, in which case multiple dimensions cannot be well summarized. The latter, correlation between environmental variables, was tested using a correlation plot (Supplementary Fig. S3). The only variables with high correlation (high correlation is considered $|r_s| \geq 0.60$) were percent shrub cover and percent non-woody cover (r_s = -0.76). Dominant water types were slightly negatively correlated between themselves, while latitude was somewhat negatively correlated with conifer presence and ruggedness.

For the generalized linear mixed model at the landscape scale, percent shrub cover, non-woody vegetation cover, and ruggedness were removed because they caused non-convergence of the regression model. For both scales of analysis, there was sufficient goodness-of-fit of global models with no evidence of overdispersion (landscape: p = 0.96, local: p = 0.96), or spatial autocorrelation (landscape: p = 0.32, local: p = 0.40). At the landscape scale, the global model received the most support (w_i = 0.67), with only two other competitive models within ΔAICc of

6.00 (Table 1). The conditional R^2 indicated a very good fit of the best model (Conditional: $R^2_{GLMM[c]} = 0.73$, Marginal: $R^2_{GLMM[m]} = 0.50$, Nakagawa & Schielzeth, 2013), in which stream coverage was the most important predictor for beaver presence (Table 2). In the model-averaged parameter estimates, streams, rivers, and small lakes had positive impacts on beaver presence while elevation and latitude had the largest negative impacts on beaver presence (Table 2). Multiple top ranked models were competitive at the local scale, with all six models in the final candidate set within a ΔAICc of 2.00 (Table 1), and no single model could effectively capture favourable habitat variables, as evidenced by the weak pseudo-R^2 value of the top model (McFadden's $R^2 = 0.14$). In the model-averaged parameter estimates, streams, rivers, and small lakes all had a strong positive impact on beaver presence (Table 2). Thus, at both the local and landscape scale, water type was always included in the top candidate models and the other environmental variables had a smaller effect.

Table 1. AICc rankings of the top six candidate models for both landscape and local scales for comparison. Generalized linear mixed models using binomial distribution and transect as a random effect were used at the landscape scale and generalized linear models were used at the local scale. The response variable in all models is beaver presence, including active and inactive sites. K represents the number of parameters, ΔAICc is the difference between the model's Akaike Information criterion corrected for small sample size (AICc) and the lowest AICc value (for the best model), and ω_i is the Akaike weight. The null model was included for comparison.

LANDSCAPE SCALE

Candidate model	K	ΔAICc	Log-likelihood	ω_i
water type + conifers present + elevation + latitude	8	0	-130.3	0.67
water type + elevation + latitude	7	1.88	-132.2	0.26
water type + conifers present + elevation	7	4.83	-133.7	0.06
water type + elevation	6	11.41	-138.0	0.00
water type + conifers present + latitude	7	12.9	-137.7	0.00
water type + conifers present	6	13.9	-139.3	0.00
null model	2	40.95	-156.8	0.00

LOCAL SCALE

Candidate model	K	ΔAICc	Log-likelihood	ω_i
water type + ruggedness	5	0	-51.5	0.24
water type	4	0.42	-52.9	0.19
water type + latitude	5	0.87	-52.0	0.15
water type + elevation	5	1.00	-52.0	0.14
water type + latitude + elevation	6	1.03	-50.9	0.14
water type + shrub cover	5	1.15	-52.1	0.13
null model	1	7.46	-59.6	0.01

Table 2. Estimates of beta coefficients for each parameter included in the top-ranking candidate models ($\Delta AIC_c \leq 6.00$ to a maximum of six models) and model-averaged beta coefficients with the associated unconditional standard error and 95% confidence interval (in italics). Covariates with 95% intervals on the model average that do not pass zero are bolded.

LANDSCAPE SCALE

Model	$\beta_{intercept}$	β_{stream}	β_{river}	$\beta_{small\ lake}$	$\beta_{latitude}$	$\beta_{elevation}$	$\beta_{conifers}$
water type + conifers + elevation + latitude	-8.57	3.36	2.29	2.23	-1.41	-1.44	1.14
water type + elevation + latitude	-8.64	3.35	2.31	2.34	-1.85	-1.65	
water type + conifers present + elevation	-8.25	3.17	2.21	2.04		-1.17	1.90
model average	**-8.57**	**3.34**	**2.29**	**2.25**	**-1.53**	**-1.48**	1.21
standard error	*1.00*	*0.80*	*0.74*	*0.81*	*0.60*	*0.40*	*0.64*
95% confidence interval	*-10.54, -6.61*	*1.78, 4.91*	*0.83, 3.75*	*0.67, 3.82*	*-2.7, -0.36*	*-2.27, -0.69*	*-0.04, 2.46*

LOCAL SCALE

Model	$\beta_{intercept}$	β_{stream}	β_{river}	$\beta_{small\ lake}$	$\beta_{latitude}$	$\beta_{elevation}$	$\beta_{ruggedness}$	β_{shrub}
water type + ruggedness	-1.33	1.98	1.59	1.57			-0.41	
water type	-1.50	2.27	1.77	1.84				
water type + latitude	-1.73	2.64	2.08	1.97	-0.35			
water type + elevation	-1.55	2.53	1.74	1.79		-0.32		
water type + latitude + elevation	-1.83	3.02	2.10	1.95	-0.41	-0.37		
water type + shrub cover	-1.71	2.59	2.07	1.96				-0.33
model average	**-1.57**	**2.44**	**1.86**	**1.82**	-0.38	-0.34	-0.41	-0.33
standard error	*0.61*	*0.84*	*0.73*	*0.83*	*0.27*	*0.25*	*0.26*	*0.27*
95% confidence interval	*-2.76, -0.37*	*0.79, 4.09*	*0.43, 3.28*	*0.19, 3.45*	*-0.92, 0.16*	*-0.84, 0.15*	*-0.91, 0.09*	*-0.86, 0.2*

Characterization of visited sites

Average length of 9 measured dams was 15 m (range = 0.8-47 m) and aquatic vegetation was observed at 11 of 38 (29%) visited sites. Among 25 lodges observed at visited sites, 14 were bank lodges built into high shorelines, 7 were low shore lodges built adjacent to flat shorelines with the top of the lodge above highest ground level, and 4 were freestanding surrounded by water (Table A3). All 4 freestanding lodges were abandoned and 2 were completely destroyed with only the base structure still intact.

Discussion

Incorporation of local observations into survey design increased detection success of beavers in western Ungava while engaging community members in wildlife monitoring and management. As beaver populations expand northwards, tracking their expansion and assessing their impacts on local wildlife have emerged as key knowledge and management priorities in Nunavik (Neelin, 2021), but the vast landscape and low beaver density (compared to densities below the treeline, summarized in Jarema et. al, 2006) renders monitoring activities logistically challenging and expensive (Danielsen et al., 2014; Christensen et al., 2020). Helicopter surveys can be made more cost-effective by first considering Inuit harvester observations and incorporating these locally identified sites together with additional systematic sampling into survey design. Inuit knowledge of wildlife and climate change impacts extends far beyond mere count data or points on a map; these observations should be considered in the context of the broader Inuit knowledge system from which they arise (Berkes et al., 2007; Gofman, 2010). Although this paper focuses mainly on the spatial distribution of local observations, it is situated within a broader project that elucidates Inuit knowledge, observations, concerns, and priorities for beaver management in Nunavik in close collaboration with local knowledge holders and Inuit-led management bodies (Neelin, 2021). Collaborative community-based monitoring has the potential to empower communities and embolden Inuit-led decision-making bodies to take informed management action and respond effectively to climate change threats (Tidball & Krasny, 2012; Ford & Pearce, 2012).

Local- and landscape-scale environmental correlates of beaver occurrence at the range edge can inform habitat suitability mapping and watercourse prioritization within survey designs. Habitat selection analysis can complement community-based monitoring approaches by extending local observations to the prediction of suitable habitats in unknown, inaccessible watercourses. The results of our habitat selection analysis highlighted the importance of dominant water body type as the main predictor of beaver presence at both scales of analysis, with beaver sign most often observed along streams, then rivers, then small lakes. Conversely, large lakes disadvantage beaver establishment because of wave exposure, often limited shoreline vegetation, and an inability to raise water levels to access flooded vegetation (Milligan & Humphries, 2010; Slough & Sadleir, 1977). Ruggedness, interpreted as a proxy for bank slope, was negatively related to beaver presence at the local scale (i.e., 500 m transect segments with low ruggedness were more likely to have beaver sign than adjacent (> 1 km away) segments with high ruggedness). Bank steepness may hinder dam-building activities and limit floodable area, limiting water-based access to shoreline vegetation (McComb et al., 1990), however, for building bank burrows, steep slopes can contribute positively by providing multiple entries into the lodges (Dieter & McCabe, 1989), if the substrate is appropriate (Slough & Sadleir, 1977; McComb et al., 1990). At a landscape scale, transects with beaver sign were at lower latitude and more likely to have coniferous tree cover, than transects without beaver sign which tended to be at higher latitude and lack conifer presence (see also Jarema, 2006). Stream gradients documented in this study were generally more gradual and less predictive of beaver presence than in other areas (Touihri et al., 2018). Stream gradients less than 6% are usually preferred for beaver dam construction and site occupancy (Northcott, 1964; Cotton, 1990; Suzuki & McComb, 1998), whereas in the current study 48 of 64 (75%) segment gradients were < 1%, and only 2 of 64 (3%) segment gradients were > 5%. Within this gradual range, stream gradient does not contribute greatly to habitat suitability for beaver presence or dam building (Northcott, 1964; Barnes & Mallik, 1997), but may be more important in other areas with higher topographic relief (Jakes et al., 2007), including Umiujaq on the Hudson coast of Nunavik where beavers are also present. Beaver presence in western Ungava was also weakly associated with watercourse width, which may simply re-emphasize the greater prevalence of beaver sign on streams than on rivers in this region. Had we analysed environmental predictors of dams separate from lodges, we may have detected an effect of watercourse gradient and width on dam presence (Touihri et al., 2018), but this separation was precluded by the general rarity of beaver sign observations. The scale-dependence of predictors of beaver presence, which includes low latitude and conifer presence predicting beaver occurrence at a landscape scale and terrain ruggedness predicting beaver occurrence at a local scale, combined with cross-scale importance of water body type, re-emphasizes the importance of scale in habitat selection research (Touihri et al., 2018; Zwolicki et al., 2019; Rather et al., 2020).

Increasing shrub cover and height are thought to be facilitating the northward expansion of beavers (Tape et al., 2018) but, in the current study, segments without beaver sign had more shrub cover than segments with beaver sign. Our reliance on shrub cover within 50 m of watercourses as a predictor variable may have omitted relevant information about shrub height or diameter (Barnes & Mallik, 1997; Myers-Smith et al., 2011) and the species composition, nutritional quality, and watercourse proximity of the shrubs that were present (Gerwing et al., 2013). Alternatively, and more directly, beaver presence may reduce shrub cover around recently occupied sites as a result of flooding and foraging (Donkor & Fryxell, 1999; Hood & Bayley, 2009). This shrub depletion possibility could be better tested by tracking shrub cover changes over time in localities where beaver remain absent, where they become newly established, and where they maintain long-term occupancy (Hood & Bayley, 2009; Hood, 2020; Ritter et al., 2020).

Inspection of beaver dams, lodges, and food caches visited on the ground in the western Ungava region of Nunavik indicated that construction of bank lodges was more common than construction of free-standing lodges surrounded by water and that aquatic vegetation was present at about one quarter of the sites. Bank lodges, which are often referred to as bank burrows or bank dens, are typically augmented with mud and sticks that cover openings and provide extra insulation (Ranawana, 1994; Müller-Schwarze, 2011). Preferential occupation of bank lodges may be influenced by bank substrate and height (Müller-Schwarze, 2011) or by insulation properties. Research by Buech et al. (1989) demonstrated that bank dens were cooler than free-standing lodges during hot summer months, but temperature in the dens were not monitored during colder months. A comparison of temperatures in free-standing versus bank lodges during winter could be informative for understanding whether beaver use of bank lodges in Nunavik may be motivated by climatic as well as geomorphological factors. Close inspection of beaver locations also revealed that aquatic vegetation was observed at over one quarter of the sites. This contrasts Jarema et al. (2006), who reported an absence of aquatic vegetation around beaver sites in southern Ungava Bay. Interviews with local harvesters in the eastern Ungava region revealed that they have been observing increasing amounts of grass-like aquatic plants growing in water bodies near Kangiqsualujjuaq, Nunavik (Neelin, 2021). Aquatic vegetation is an important part of beaver diets at the northern edge of their range, so increases in aquatic vegetation may help them colonize new areas (Milligan & Humphries, 2010; Allen, 1982; Howard & Larson, 1985). Aquatic vegetation is difficult to observe during helicopter surveys or from remote sensing methods, but a better understanding of the distribution and diversity of aquatic vegetation in Nunavik water bodies may be relevant to patterns of beaver occupancy and persistence in subarctic and arctic environments.

Remote sensing to detect beaver presence, habitat, and impacts has been successfully explored in many regions, including above the Alaskan treeline (Tape et al., 2018; Jones et al., 2020), and can successfully capture flooding events caused by dams (Townsend & Butler, 1996; Anderson & Bonner, 2014; Martin et al., 2015; Morrison et al., 2015; Pasquarella et al., 2016; Henn et al., 2016). The possibility of using remote detection of beaver presence in Nunavik is just in the early exploration stages (Caron, 2020) and offers a promising opportunity for the collection of more sites of positive beaver presence, for the validation of predictions when extrapolating this model, and for assessing impacts of beaver presence in this region. The small number of dams observed during the helicopter survey (observed in only 26 out of 40 colonies) will make this approach more challenging, but not impossible (Henn et al., 2016). In any case, concerns raised by communities regarding beaver presence are usually related to dam construction, therefore those detections are prioritized for management decision-making (Tape et al., 2018; Neelin, 2021).

The beaver is just one of many climate-tracking species that are catalysts of Arctic ecosystem transformation. This project offers an example of how investigation of the distribution of these species can be studied, most effectively through knowledge co-production and local observations to document their spread and impact. This approach facilitates the daunting task of detecting ecological abnormalities in a vast and remote region while engaging communities in a way that supports indigenous-led management action.

Conclusion

Habitat selection has long been an important instrument in the toolbelt of wildlife management authorities. In areas of beaver introduction, understanding habitat selection helps identify areas where successful settlement may occur (Ritter et al., 2020). Although the research presented here serves as a useful preliminary characterization of beaver presence in this region, possible improvements to the model could include adding a predictor variable to describe shrub height and cover more precisely, including an indicator of aquatic vegetation presence, gathering more detailed information from community-based monitoring about dates of beaver colonization events in order to characterize habitat before and after their modifications, and increasing the number of observed occupied sites in order to improve the power and accuracy of predictive models. In Nunavik, understanding beaver habitat selection can complement community-based monitoring approaches by extending local observations to the prediction of suitable habitats in inaccessible regions. This can help economize management projects when concerns are raised about their impact on Arctic char systems (Neelin, 2021).

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Supplementary Materials

Supplementary Table S1. Independent variables considered in this research, methods used for their calculation, sources of data, and key citations referencing their significance in previous research on beaver habitat suitability.

Variable	Methods	Source(s) of data	Key citations
Shrub cover within 50 m of water bodies	MFFP vegetation classes were re-classified with shrubs in one category. Percent cover was calculated along the 50 m buffer of the CanVec watercourses that intersected with the 400m buffer of the flown helicopter transect using the zonal histogram function in QGIS.	Land classes from MFFP vegetation data: *www.donneesquebec.ca*. Water polygons from CanVec Series - Topographic Data of Canada (Natural Resources Canada): *open.canada.ca*.	Slough & Sadleir, 1977; Suzuki & McComb, 1998; Jensen et al., 2001
Conifer presence within 50 m of water bodies	MFFP vegetation classes were categorized for all conifer categories into one category: “conifers”. If there was any presence of conifers in the 50 m buffer of the CanVec watercourses that intersected with the 400 m buffer of the flown helicopter transect, the value was "conifers present", regardless of percent cover.	Land classes from MFFP vegetation data *www.donneesquebec.ca*	Jarema, 2006
Non-woody vegetation cover within 50 m	MFFP vegetation classes were categorized for all non-woody vegetation categories into one category (including “subarctic lichen-heath”, “saltwater marsh”, “bare ground”, “Arctic fen or wet tundra”, “rock outcrops and fragments”, “boulder fields”, and “uniform fen”). Percent cover were calculated along the 50 m buffer of the CanVec watercourses that intersected with the 400m buffer of the flown helicopter transect.	Land classes from MFFP vegetation data *www.donneesquebec.ca*	Curtis & Jensen, 2004; Lapointe St-Pierre, 2017
Elevation	Mean elevation calculated from Digital Elevation Model	DEM accessed from Natural Resources	Henn et al., 2016

	in 50 m buffer of the CanVec watercourses that intersected with the 400 m buffer of the flown helicopter transect	Canada: *ftp.maps.canada.ca*	
Latitude	Latitude was extracted from GPS data from the helicopter survey for the midpoint of each transect	Original shapefile created by importing Garmin data	Jarema, 2006; Jarema et al., 2009
Ruggedness within 50 m	Ruggedness was calculated from the DEM raster layer using the QGIS Raster Terrain Analysis tool. Mean ruggedness in the 50m buffer around the water bodies was used as a proxy for bank slope (bank steepness).	DEM accessed from Natural Resources Canada: *ftp.maps.canada.ca*	Novak, 1987; Dieter & McCabe, 1989; McComb et al., 1990
Water body type	Water was categorized into one of four classes: streams, rivers, small lakes (less than 2 km2), and large lakes (2 km2 or larger). Stream categorization included the primary and secondary watercourse classifications, which were already defined in the CanVec watercourse file attributes, while the river class was a consolidation of all features in the CanVec water body file that were classified as watercourse (i.e. large enough to be a polygon but not classified as a lake). The water body type for each segment was the dominant class that was present, based on the percentage of each water class along the shore, so that wide water bodies would not be overrepresented.	CanVec Series from Topographic Data of Canada (Natural Resources Canada), from *open.canada.ca*	Jarema, 2006; Henn et al., 2016
Watercourse **gradient**	Gradients of watercourses were calculated using the elevations from the DEM for the points at the extremities of the watercourse within one segment and the distance	DEM accessed from Natural Resources Canada: *ftp.maps.canada.ca*, CanVec Series from Topographic Data of	Slough & Sadleir, 1977; Howard & Larson, 1985; Beier & Barrett, 1987;

	between them (vertical drop divided by distance).	Canada (Natural Resources Canada), from *open.canada.ca*	Cotton, 1990; Suzuki & McComb, 1998; Jakes et al., 2007; Cox & Nelson, 2009; Anderson & Bonner, 2014; St-Pierre et al., 2017; Dittbrenner et al., 2018; Ritter et al., 2020
Average watercourse **width**	Average width was calculated for each segment using the area of the CanVec watercourse vectors within one segment divided by the length of the centre line of that watercourse.	CanVec Series from Topographic Data of Canada (Natural Resources Canada), from *open.canada.ca*	Howard & Larson, 1985; Beier & Barrett, 1987; Suzuki & McComb, 1998; Dittbrenner et al., 2018; Ritter et al., 2020

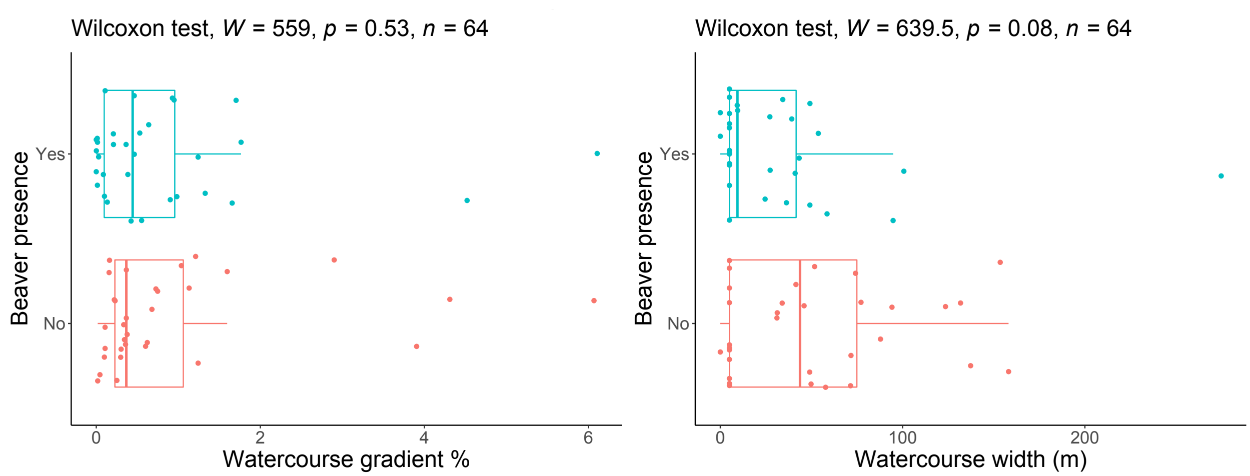
Supplementary Table S2. Table of observations from helicopter survey, including sign, beaver colony ID, transect number, block ID, village associated with the block, and whether it was an inactive or active colony.

Longitude	Latitude	Sign	Colony	Transect	Block	Nearby village	Active
-69.86	59.09	Partial dam	C40	T41	A-LI	Aupaluk	Inactive
-69.65	58.65	Dam	C04	T19	T-LI	Tasiujaq	Inactive
-69.65	58.65	Lodge	C04	T19	T-LI	Tasiujaq	Inactive
-69.65	58.65	Dam	C04	T19	T-LI	Tasiujaq	Inactive
-69.65	58.65	Lodge	C04	T19	T-LI	Tasiujaq	Inactive
-69.65	58.65	Dam	C04	T19	T-LI	Tasiujaq	Inactive
-69.66	58.63	Lodge	C05	T19	T-LI	Tasiujaq	Active
-69.66	58.63	Food cache	C05	T19	T-LI	Tasiujaq	Active
-69.67	58.62	Dam	C06	T19	T-LI	Tasiujaq	Active
-69.67	58.62	Lodge	C06	T19	T-LI	Tasiujaq	Active

-69.67	58.62	Food cache	C06	T19	T-LI	Tasiujaq	Active
-69.67	58.62	Lodge	C07	T19	T-LI	Tasiujaq	Inactive
-69.67	58.62	Lodge	C07	T19	T-LI	Tasiujaq	Inactive
-69.67	58.62	Lodge	C07	T19	T-LI	Tasiujaq	Inactive
-69.67	58.62	Food cache	C07	T19	T-LI	Tasiujaq	Inactive
-69.67	58.62	Dam	C07	T19	T-LI	Tasiujaq	Inactive
-69.67	58.61	Dam	C08	T19	T-LI	Tasiujaq	Inactive
-69.67	58.61	Lodge	C08	T19	T-LI	Tasiujaq	Inactive
-69.63	58.64	Dam	C09	T20	T-LI	Tasiujaq	Active
-69.63	58.64	Lodge	C09	T20	T-LI	Tasiujaq	Active
-69.63	58.64	Food cache	C09	T20	T-LI	Tasiujaq	Active
-70.10	58.33	Lodge	C15	T28	T-LI	Tasiujaq	Active
-70.10	58.33	Lodge	C15	T28	T-LI	Tasiujaq	Active
-70.10	58.33	Food cache	C15	T28	T-LI	Tasiujaq	Active
-70.07	58.37	Dam	C16	T28	T-LI	Tasiujaq	Active
-70.07	58.37	Lodge	C16	T28	T-LI	Tasiujaq	Active
-70.07	58.37	Food cache	C16	T28	T-LI	Tasiujaq	Active
-70.06	58.38	Lodge	C17	T28	T-LI	Tasiujaq	Active
-70.21	58.32	Lodge	C18	T29	T-LI	Tasiujaq	Active
-70.21	58.32	Lodge	C18	T29	T-LI	Tasiujaq	Active
-70.21	58.32	Lodge	C18	T29	T-LI	Tasiujaq	Active
-70.21	58.32	Dam	C18	T29	T-LI	Tasiujaq	Active
-70.26	58.34	Lodge	C20	T30	T-LI	Tasiujaq	Active
-70.26	58.34	Lodge	C20	T30	T-LI	Tasiujaq	Active
-70.26	58.34	Dam	C20	T30	T-LI	Tasiujaq	Active
-70.26	58.34	Lodge	C20	T30	T-LI	Tasiujaq	Active
-70.26	58.34	Food cache	C20	T30	T-LI	Tasiujaq	Active
-70.26	58.34	Food cache	C21	T30	T-LI	Tasiujaq	Active
-70.25	58.37	Dam	C22	T30	T-LI	Tasiujaq	Inactive
-70.25	58.37	Lodge	C22	T30	T-LI	Tasiujaq	Inactive
-70.24	58.37	Lodge	C23	T30	T-LI	Tasiujaq	Inactive
-70.24	58.37	Food cache	C23	T30	T-LI	Tasiujaq	Inactive
-70.24	58.37	Partial dam	C23	T30	T-LI	Tasiujaq	Inactive
-70.24	58.37	Partial dam	C23	T30	T-LI	Tasiujaq	Inactive
-70.24	58.37	Lodge	C24	T30	T-LI	Tasiujaq	Active
-70.24	58.37	Dam	C24	T30	T-LI	Tasiujaq	Active
-70.24	58.37	Lodge	C25	T30	T-LI	Tasiujaq	Inactive
-70.24	58.38	Partial dam	C25	T30	T-LI	Tasiujaq	Inactive
-70.24	58.38	Lodge	C26	T30	T-LI	Tasiujaq	Active
-70.24	58.38	Food cache	C26	T30	T-LI	Tasiujaq	Active

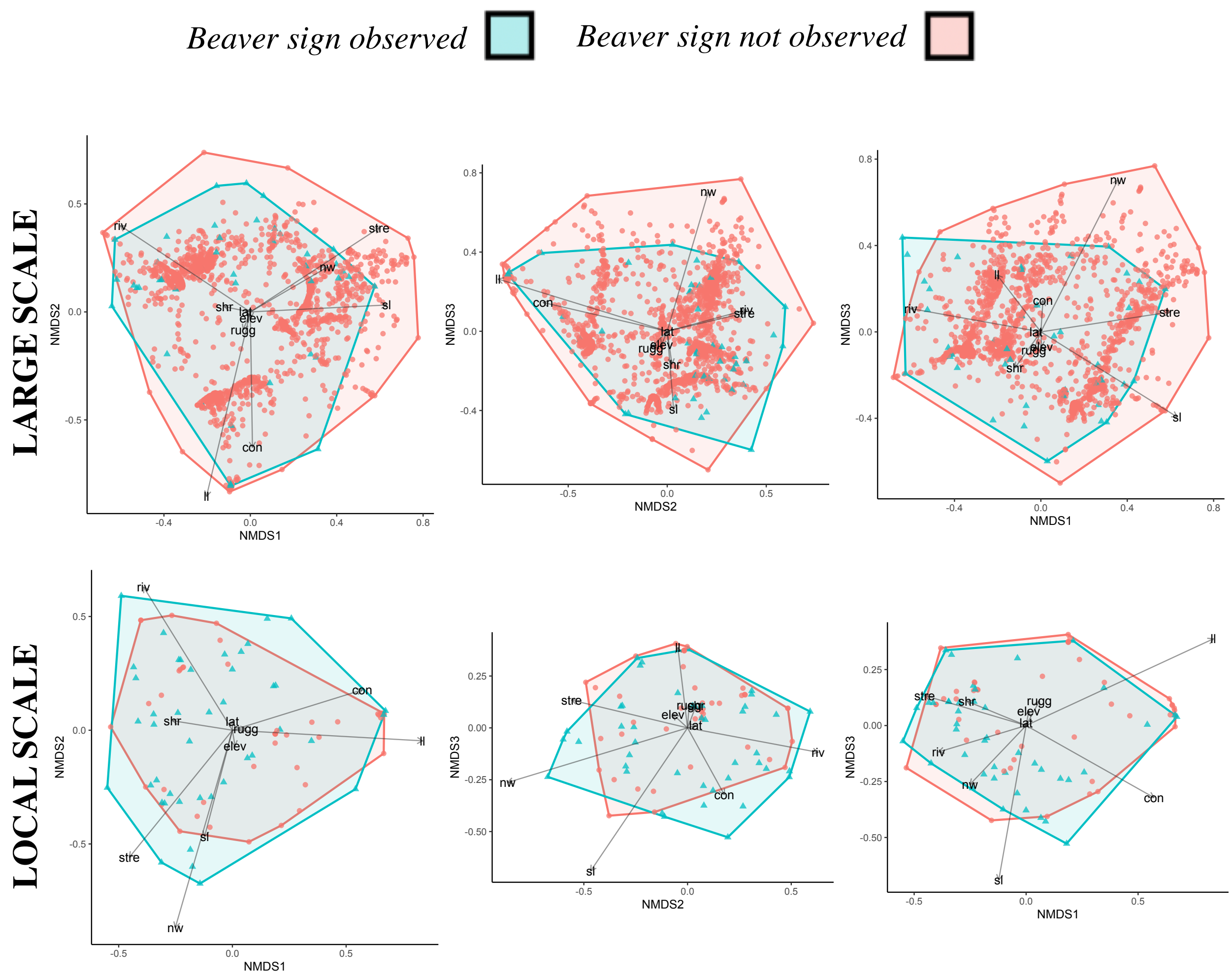
-70.24	58.39	Lodge	C27	T30	T-LI	Tasiujaq	Active
-70.24	58.39	Food cache	C27	T30	T-LI	Tasiujaq	Active
-70.28	58.78	Dam	C28	T32	T-LI	Tasiujaq	Active
-70.27	58.78	Lodge	C28	T32	T-LI	Tasiujaq	Active
-70.27	58.78	Food cache	C28	T32	T-LI	Tasiujaq	Active
-70.18	58.74	Lodge	C29	T33	T-LI	Tasiujaq	Active
-70.18	58.74	Dam	C29	T33	T-LI	Tasiujaq	Active
-70.30	58.78	Lodge	C30	T34	T-LI	Tasiujaq	Inactive
-70.32	58.78	Partial dam	C31	T34	T-LI	Tasiujaq	Active
-70.33	58.78	Partial dam	C31	T34	T-LI	Tasiujaq	Active
-70.33	58.78	Lodge	C31	T34	T-LI	Tasiujaq	Active
-70.33	58.78	Lodge	C31	T34	T-LI	Tasiujaq	Active
-70.35	58.79	Dam	C32	T34	T-LI	Tasiujaq	Inactive
-70.35	58.79	Partial dam	C32	T34	T-LI	Tasiujaq	Inactive
-70.20	58.82	Dam	C33	T37	T-LI	Tasiujaq	Active
-70.20	58.82	Dam	C33	T37	T-LI	Tasiujaq	Active
-70.20	58.83	Lodge	C33	T37	T-LI	Tasiujaq	Active
-70.20	58.83	Food cache	C33	T37	T-LI	Tasiujaq	Active
-70.03	58.88	Dam	C34	T38	A-A	Aupaluk	Inactive
-70.02	58.93	Dam	C35	T38	A-A	Aupaluk	Inactive
-70.02	58.93	Dam	C35	T38	A-A	Aupaluk	Inactive
-70.02	58.95	Dam	C36	T38	A-A	Aupaluk	Active
-70.02	58.95	Lodge	C36	T38	A-A	Aupaluk	Active
-70.02	58.95	Food cache	C36	T38	A-A	Aupaluk	Active
-70.06	58.94	Dam	C37	T38	A-A	Aupaluk	Active
-70.07	58.95	Partial dam	C37	T38	A-A	Aupaluk	Active
-70.07	58.95	Lodge	C37	T38	A-A	Aupaluk	Active
-70.07	58.95	Food cache	C37	T38	A-A	Aupaluk	Active
-70.07	58.94	Lodge	C38	T38	A-A	Aupaluk	Active
-70.08	58.94	Dam	C38	T38	A-A	Aupaluk	Active
-70.08	58.94	Dam	C38	T38	A-A	Aupaluk	Active
-70.08	58.94	Dam	C38	T38	A-A	Aupaluk	Active
-70.08	58.94	Dam	C38	T38	A-A	Aupaluk	Active
-70.08	58.94	Dam	C38	T38	A-A	Aupaluk	Active
-70.08	58.94	Lodge	C38	T38	A-A	Aupaluk	Active
-70.08	58.94	Lodge	C38	T38	A-A	Aupaluk	Active
-70.08	58.94	Food cache	C38	T38	A-A	Aupaluk	Active
-70.09	58.94	Lodge	C38	T38	A-A	Aupaluk	Active
-70.09	58.94	Dam	C39	T38	A-A	Aupaluk	Active
-70.09	58.94	Lodge	C39	T38	A-A	Aupaluk	Active

-70.09	58.94	Food cache	C39	T38	A-A	Aupaluk	Active
-69.58	58.52	Lodge	C10	T21	T-A	Tasiujaq	Active
-69.58	58.52	Food cache	C10	T21	T-A	Tasiujaq	Active
-69.66	58.43	Lodge	C11	T22	T-A	Tasiujaq	Active
-69.66	58.43	Food cache	C11	T22	T-A	Tasiujaq	Active
-69.91	58.32	Lodge	C12	T24	T-A	Tasiujaq	Inactive
-70.13	58.21	Dam	C13	T27	T-A	Tasiujaq	Active
-70.13	58.21	Food cache	C13	T27	T-A	Tasiujaq	Active
-70.13	58.21	Dam	C13	T27	T-A	Tasiujaq	Active
-70.13	58.21	Dam	C13	T27	T-A	Tasiujaq	Active
-70.11	58.28	Lodge	C14	T27	T-A	Tasiujaq	Inactive
-70.11	58.29	Lodge	C14	T27	T-A	Tasiujaq	Inactive
-69.15	58.48	Lodge	C01	T02	T-B	Tasiujaq	Inactive
-69.98	58.14	Lodge	C02	NA	NA	NA	Active
-69.98	58.14	Food cache	C02	NA	NA	NA	Active
-70.00	58.22	Lodge	C03	NA	NA	NA	Active
-70.24	58.29	Dam	C19	NA	NA	NA	Active
-70.24	58.29	Dam	C19	NA	NA	NA	Active
-70.24	58.29	Food cache	C19	NA	NA	NA	Active

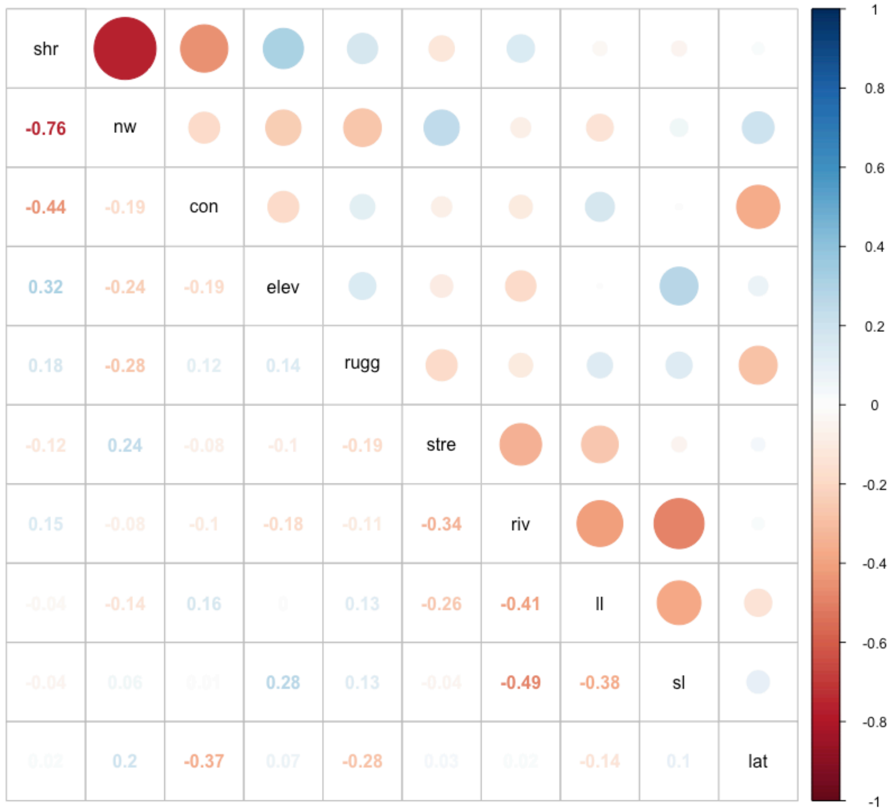


Supplementary Fig. S1. Boxplots and summaries of statistical results of non-normally distributed watercourse descriptor variables to compare differences in distributions between segments with beaver observations and segments without beaver observations. This was analyzed on streams and rivers at the landscape scale only, using the unpaired (two-sample)

Wilcoxon test, since local scale could not be analyzed due to disproportion of watercourses to lakes between neighbouring segments.



Supplementary Fig. S2. Non-metric multidimensional scaling (NMDS) ordination results representing environmental variables using three new dimensions and the relative loading of each variable at the landscape scale and local scale. Environmental variables include percent shrub cover (**shr**), percent non-woody cover (**nw**), coniferous presence (**con**), mean elevation (**elev**), mean ruggedness (**rugg**), watercourse types (stream: **stre**, river: **riv**, large lake: **ll**, small lake: **sl**), and latitude (**lat**).



Supplementary Fig. S3. Correlation matrix between candidate variables, represented by both circles and the numerical correlation coefficients. Negative correlations are represented in red and correlation is proportional to both size of circle and transparency of colour. Environmental variables include percent shrub cover (**shr**), percent non-woody cover (**nw**), presence of conifers (**con**), mean elevation (**elev**), mean ruggedness (**rugg**), watercourse types (stream: **stre**, river: **riv**, large lake: **ll**, small lake: sl**)**, and latitude (**lat**).

Supplementary Table S3: Table of observations from ground visits, including the sign, type of lodge, status, and whether aquatic vegetation was present.

Dams					
Latitude	**Longitude**	**Sign**	**Length**	**Status**	**Aquatic vegetation**
58.37	-70.07	Dam	0.80 m	Active	Yes
58.37	-70.07	Dam	3.60 m	Active	No
58.62	-69.67	Dam	4.00 m	Abandoned	No
58.42	-70.25	Dam	8.80 m	Abandoned	No
58.62	-69.67	Dam	9.00 m	Abandoned	Yes

58.37	-70.24	Dam	10.80 m	Active	No
58.42	-70.25	Dam	11.00 m	Abandoned	No
58.61	-69.67	Dam	38.00 m	Abandoned	No
58.74	-70.18	Dam	47.20 m	Active	No
58.37	-70.24	Dam		Abandoned	No
58.37	-70.25	Dam		Abandoned	No
58.65	-69.65	Dam		Abandoned	Yes
58.37	-70.24	Dam		Active	Yes
Lodges					
Latitude	**Longitude**	**Sign**	**Lodge type**	**Status**	**Aquatic vegetation**
58.42	-70.25	Lodge	Bank	Abandoned	No
58.48	-69.15	Lodge	Bank	Abandoned	No
58.62	-69.67	Lodge	Bank	Abandoned	No
58.14	-69.98	Lodge	Bank	Active	No
58.22	-70.00	Lodge	Bank	Active	No
58.32	-70.21	Lodge	Bank	Active	No
58.32	-70.21	Lodge	Bank	Active	No
58.32	-70.21	Lodge	Bank	Active	No
58.37	-70.24	Lodge	Bank	Active	No
58.37	-70.24	Lodge	Bank	Active	Yes
58.37	-70.24	Lodge	Bank	Active	Yes
58.37	-70.24	Lodge	Bank	Active	Yes
58.38	-70.06	Lodge	Bank	Active	Yes
58.78	-70.27	Lodge	Bank	Active	No
58.61	-69.67	Lodge	Low shore	Abandoned	No
58.65	-69.65	Lodge	Low shore	Abandoned	Yes
58.32	-70.21	Lodge	Low shore	Active	No
58.37	-70.07	Lodge	Low shore	Active	No
58.37	-70.24	Lodge	Low shore	Active	No
58.39	-70.23	Lodge	Low shore	Active	No
58.39	-70.23	Lodge	Low shore	Active	Yes
58.42	-70.25	Lodge	Free-standing	Abandoned	No
58.42	-70.25	Lodge	Free-standing	Abandoned	No
58.62	-69.67	Lodge	Free-standing	Abandoned	No
58.65	-69.65	Lodge	Free-standing	Abandoned	Yes

GENERAL DISCUSSION

The northward expansion of wildlife distributions due to climate change is restructuring ecosystems, modifying landscapes and creating novel species interactions that are not clearly understood (Gilman, 2010; Meredith et al., 2019; Williams & Jackson, 2007). Although Urban (2020) argues that climate-tracking species will have fewer novel interactions and thus less adverse impacts than an artificially transplanted invasive species, the Arctic tundra is a unique and distinct ecosystem with a vulnerable and often naïve biome (Meredith et al., 2019). Inuit and researchers are already expressing concerns regarding the far-reaching impacts of beavers on the Arctic landscape, such as permafrost thaw stimulated by beaver dams (Jones et al., 2020; Tape et al., 2018) and new interactions between beavers and Arctic char. Urban (2020) also recommends that species experiencing range displacements due to climate change should be facilitated as climate refugees so that whole ecological communities can shift northwards into their newly accommodating habitat. From a purely ecological, temperate region perspective, Urban's logic may be convincing, but the implications of this management approach on Arctic regions and Indigenous communities are critically understated. Arctic wildlife, especially terrestrial species, are near to the northern limit of the land mass and may experience the effect of "Arctic squeeze" (i.e. habitat loss, Meredith et al., 2019) when they are displaced by encroaching southern species. Nunavimmiut are particularly vulnerable to ecosystem shifts because of high food insecurity and strong reliance on subsistence harvesting in Nunavik (Downing & Cuerrier, 2011). Country foods are appreciated for more than just their nutritional value; they have an important cultural, historical, and social significance that cannot be fully replaced with store-bought foods or new wildlife harvests (Collings et al., 1998; Nickels et al., 2005; Rosol et al., 2016; Wein et al., 1996). This thesis re-orients the climate-tracking wildlife dialogue towards Inuit communities in an effort to provide information, tools, and tangible support to facilitate Inuit-led decision making, management, and adaptation strategies.

Inuit and scientific knowledge

This work was co-produced with local organizations and harvesters in an effort to create new knowledge that would be relevant and beneficial to Nunavimmiut. The project began with an internship conducted with an Inuit organization, which provided an opportunity to become familiar with the political landscape and wildlife management network in Nunavik while making a tangible contribution to the host organization. The internship also provided an opportunity to learn about local priorities and outline relevant research goals while becoming familiarized with the culture, language, and norms. Meetings with partners refined goals and methodologies that were appropriate and acceptable to the communities. Inuit knowledge interviews outlined priority areas and shared beaver sign observations, which were used to design survey transects, while an Inuit pilot and crew gave insight into traditional areas, beaver observations, and surrounding environments during the survey. This survey was followed by specific questionnaires and communication of results to community members, which gave them opportunities to contribute to interpretation of results. This knowledge coproduction approach is recommended by ITK (2018) and by Pedersen et al. (2020) and was further improved through community engagement in everyday life. Living in Tasiujaq, Nunavik during and after this research project allowed these engagement activities to be less rushed, communication to come at the community's pace, and the research to be easily accessible. In addition, employment with the Hunting Fishing Trapping Association after completion of graduate studies facilitated a continued availability to respond to harvesters' concerns about beavers and a sustained dialogue about mitigation strategies. While this is not possible for every graduate student, my experience speaks to the benefits of a sustained relationship with community that extends beyond the start and end of data collection, allowing the community input into study focus and design, as well as knowledge application and subsequent projects. A thesis project has a start and an end date, whereas Inuit knowledge, climate change concerns, and adaptation efforts do not.

The intersection of Inuit knowledge and scientific approaches in this research revealed how the two perspectives can complement each other to produce a more holistic understanding of the range shifts, habits, and impacts of climate-tracking species. Beaver observations at high latitudes are usually sporadic and the temporal pattern of their northward expansion has rarely been documented (Tape et al., 2016), though sometimes predicted (Jarema, 2006; Jung et al., 2017). Satellite images have been successfully used to create a basic timeline of damming events (Tape et al., 2018), but Inuit knowledge holders can offer further insights such as failed colonization attempts, observed behaviour, social-ecological context at the time of beaver appearances, and impacts on Inuit livelihood. Failed colonization attempts, including observations of beavers swimming along watercourses without any subsequent building activity, may be indicative of possible colonization routes if the habitat ameliorates (from the perspective of beaver habitat requirements) enough to support future settlement. Beaver behaviour observed by harvesters included swimming along the shore of Ungava Bay. Beaver presence in saltwater is seldom documented but has important implications as a potential dispersal route between freshwater systems (Jung et al., 2017). Dispersal is a normal part of every beaver's transition to adulthood, but long-distance dispersal at the northern range limit may be more common during periods of dramatic social-ecological change, such as climate change, or, in the case of beavers moving higher in the Nunavik region in 1960s, possibly the formation of hydroelectric dams or the release of hunting pressure from forced settlement of the Cree and Naskapi. Inuit knowledge provided a greater depth of understanding of beaver range expansion, beyond dates or locations on a map, and survey methods were able to complement that knowledge by exploring a larger area of the western Ungava region, including watercourses that were largely inaccessible to harvesters travelling by boat and snow machine. Surveys were able to confirm which of the locally observed sites were still active, note if beaver sign was still recognizable, and characterize the sites in a systematic manner. The analysis of beaver habitat selection in Nunavik identified environmental variables associated with beaver presence and which can contribute to predictive models intended to inform Inuit-led monitoring efforts beyond frequented watercourses. Furthermore, Inuit knowledge provides insight into the broader context of the ecosystem into which beavers are inserting themselves, including the behaviour and abundance of other species, the direction and flow of watercourses, the presence of specific vegetation types, and the associations between these separate elements. Thus, Inuit harvesters are often the first to detect abnormalities, to draw connections, and to understand the implications of these changes for the ecosystem as a whole. Inuit knowledge and scientific approaches, considered in conjunction, offered a more detailed and holistic understanding of species range expansion than any single knowledge system or scientific approach could achieve alone.

Future directions

Nunavimmiut are finding innovative ways to manage and adapt to climate change on their own, but researchers have the opportunity to come alongside and support these Inuit-led efforts when community interest is expressed. Through the co-production of knowledge demonstrated in this research, Inuit management organizations engaged directly in the research process and are continuing to investigate the question beyond the timeline and financing of this specific thesis. Recommendations mentioned in this research included further research on beaver distribution, financial incentives to encourage beaver trapping, and knowledge sharing workshops with Cree trappers, which offers a long-term adaptive solution. The research presented in this thesis sets a foundation of understanding of beaver expansion focused on the Ungava Bay region. Local harvesters in Umiujaq, in the Hudson Bay region, have also expressed concerns regarding beaver range expansion and could benefit from inclusion in future research projects. The results and collaborations from this study have already birthed new initiatives, including an effort to remotely detect beaver presence in Nunavik (Caron, 2020), beaver skull collection for diet analysis, and an Inuit-led beaver working group. This pattern of beaver range expansion is occurring across northern North America and similar concerns are being raised by various Indigenous groups (Brubaker et al., 2011; Heredia Vazquez, 2019; Joling, 2011; Wangkhang, 2017). Communicating these results widely and facilitating collaborative research between regions will help equip harvesters for effective mitigation and adaptation strategies internationally. Adaptation policy and action that is informed by Indigenous knowledge, led by Indigenous groups, and supported by researchers is critical in order to establish long term solutions to address the arrival of this novel species in the Arctic.

CONCLUSION

The objectives of this thesis were to 1) characterize the change in beaver distribution and associated habitat characteristics in Nunavik, 2) document Inuit knowledge about beaver expansion and the impact on Inuit food security, and 3) identify adaptation strategies to minimize these impacts. These objectives were accomplished through a mixed method approach that integrated scientific and Inuit knowledge methods, including an aerial survey, regression models, open-ended interviews with harvesters and those involved in wildlife management, and a short answer questionnaire with a diverse group of community members. Beavers were first observed in Nunavik in the 1950s and 1960s, and populations in the western Ungava region expanded northward towards Aupaluk and Kangirsuk more recently. The habitat selection analysis underlined the importance of dominant water body type as a predictor of beaver presence at both a landscape and local scale of analysis, with beaver sign most often observed along streams, then rivers, then small lakes and less commonly on large lakes. Other environmental predictors were scale-dependent; low latitude and conifer presence predicted beaver occurrence at a landscape scale and low terrain ruggedness predicted beaver occurrence at a local scale. This habitat selection analysis set a foundation for habitat suitability mapping and watercourse prioritization to inform future surveys and management planning activities. Communities prioritized beaver management because of their concerns regarding the impact of beaver dams on Arctic char, particularly their upriver migration during the fall, and associated impacts on country food use of Arctic char and general food security. Many Tasiujaq community members did not wish to include beaver meat in their regular diet because it is not a traditional country food but appreciated beaver fur for its warmth in winter clothing. Recommended management strategies included further research on their distribution and impacts across Nunavik, increased collaboration between organizations, knowledge and food sharing with other indigenous groups, and increased incentives for beaver trapping.

This research has integrated local knowledge with ecological research to identify and mobilize mitigation strategies in order to protect the integrity of local Indigenous food systems, enhance food security, and contribute to community well-being in an era of rapid environmental change. This project responds to knowledge needs and priorities that have been expressed by Nunavik communities but have not previously been prioritized by academic researchers. Thus far, beaver impacts in the Arctic have been considered primarily from an ecological perspective and have not explored their cultural and social impacts related to indigenous food systems. This thesis sets a foundation for research on other species that are expanding and establishing in northern regions due to climate change. Nunavimmiut (the Inuit of Nunavik) have identified species such as Atlantic salmon, suckers (*Catostomus spp.*), black bears (*Ursus americanus*), moose (*Alces alces*) and killer whales (*Orcinus orca*) as priorities for climate change and food security research as they expand northwards and impact local wildlife. This project also sets a precedent for community-engaged, collaborative climate change research that incorporates local and scientific knowledge in support of Inuit self-determination and wildlife management.

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