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Do beaver ponds increase methane emissions along Arctic tundra streams?

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Abstract

Beaver engineering in the Arctic tundra induces hydrologic and geomorphic changes that are favorable to methane (CH_4) production. Beaver-mediated methane emissions are driven by inundation of existing vegetation, conversion from lotic to lentic systems, accumulation of organic rich sediments, elevated water tables, anaerobic conditions, and thawing permafrost. Ground-based measurements of CH_4 emissions from beaver ponds in permafrost landscapes are scarce, but hyperspectral remote sensing data (AVIRIS-NG) permit mapping of 'hotspots' thought to represent locations of high CH_4 emission. We surveyed a 429.5 km^2 area in Northwestern Alaska using hyperspectral airborne imaging spectroscopy at $\sim$5 m pixel resolution (14.7 million observations) to examine spatial relationships between CH_4 hotspots and 118 beaver ponds. AVIRIS-NG CH_4 hotspots covered 0.539% (2.3 km^2) of the study area, and were concentrated within 30 m of waterbodies. Comparing beaver ponds to all non-beaver waterbodies (including waterbodies >450 m from beaver-affected water), we found significantly greater CH_4 hotspot occurrences around beaver ponds, extending to a distance of 60 m. We found a 51% greater CH_4 hotspot occurrence ratio around beaver ponds relative to nearby non-beaver waterbodies. Dammed lake outlets showed no significant differences in CH_4 hotspot ratios compared to non-beaver lakes, likely due to little change in inundation extent. The enhancement in AVIRIS-NG CH_4 hotspots adjacent to beaver ponds is an example of a new disturbance regime, wrought by an ecosystem engineer, accelerating the effects of climate change in the Arctic. As beavers continue to expand into the Arctic and reshape lowland ecosystems, we expect continued wetland creation, permafrost thaw and alteration of the Arctic carbon cycle, as well as myriad physical and biological changes.

1. Introduction

The Arctic is warming four times faster than the global average [1] causing cascading effects on landscapes and ecosystems [2–4]. Warmer air temperatures in the northern high latitudes are affecting permafrost, vegetation, and wildlife in the Arctic [5–10]. Modeling studies indicate that greenhouse gas emissions following permafrost thaw will amplify current rates of atmospheric warming, a process known as the permafrost-carbon feedback [11]. North American beavers (*Castor canadensis*) have colonized the Arctic tundra during the last half-century [12]. In the Arctic, beaver dams often trigger local inundation and subsequent permafrost thaw [12–14], a mechanism known to mobilize permafrost carbon (C) to the atmosphere in the form of the greenhouse gasses carbon dioxide (CO_2) and methane (CH_4). Short-term and long-term measurements linking beaver pond construction in the Arctic with CH_4 release are lacking. Here, we use remotely sensed data to examine the potential for beaver colonization in the tundra to increase Arctic CH_4 emissions.

Northern permafrost regions contain vast amounts of soil organic carbon. Permafrost is thawing across these regions, evident as increased thaw slumps [15], formation and disappearance of thermokarst lakes [16], thawing ice wedge polygonal ground [17], increased erosion rates, and warming temperatures in boreholes. Permafrost thaw surrounding streams and rivers is evident in the altered timing and partitioning of streamflow [18]. Geochemical signatures of increased subsurface compared to surface flow indicate that thawing permafrost enhances flowpaths and connectivity underneath stream channels [19]. These processes are expected to continue with future warming, but non-linearities associated with abrupt thaw processes hamper predictions of the strength of the permafrost-carbon feedback [20]. As beavers colonize streams in the Arctic, they construct ponds along streams, likely enhancing subsurface flows [21] and advective heat transfer to permafrost.

When permafrost thaw induces subsidence and ponding, anoxic conditions favor the microbial conversion of thawed permafrost organic C to greater quantities of CH_4 as opposed to CO_2 [22, 23]. Though the fine-scale spatiotemporal variability of total CH_4 flux remains difficult to quantify *in-situ* at landscape scales, recent advances in airborne remote sensing have quantified CH_4 hotspot occurrences across regional scales [24, 25]. Hotspot behavior is indicative of sites with intensive biogeochemical activity that are likely complemented by biotic factors (e.g. vegetation and microbial metabolism) and abiotic factors (e.g. physical thermokarst characteristics and labile C) that drive extreme emissions [25]. Beaver colonization and the associated flooding and hydrologic changes alter adjacent vegetation composition, conflating physical and biologic drivers of CH_4 emissions.

North American beavers are a keystone species whose engineering is known to heavily influence streams, rivers, riparian corridors, and lakes in North America, Eurasia, and South America [26]. Beavers induce hydrologic and geomorphic alteration of the landscape by flooding terrestrial surfaces and converting lotic to lentic environments, which alter biogeochemical cycling in non-permafrost temperate ecosystems [27]. Many beavers build dams to increase the size and depth of waterbodies to elude predators, access upland forage areas, facilitate transport of wood for forage and dam construction, increase winter unfrozen water habitat, and promote early successional forage species [28].

Through their engineered expansion of waterbodies, beaver dams often increase water depth, flood nearby vegetation, raise groundwater levels, and perennially thaw regions that would otherwise freeze in winter, all of which are known mechanisms for promoting CH_4 emissions. Furthermore, the presence of beaver dams drives accumulation of organic-rich sediment in impounded stream reaches, which is often hundreds of times greater than that found in free-flowing channels [29]. Sediment accumulation in lentic environments promotes microbial decomposition of organic matter, leading to anoxic conditions suitable for methanogenesis. As a result of a likely combination of these factors, beaver ponds have been shown throughout the non-permafrost region to emit >30 times more CH_4 per unit area than other types of wetlands, lakes, and lotic systems [27, 30–34]. While information on northern beaver pond CH_4 emissions are scarce, theory suggests that emissions may be higher yet in beaver ponds beneath which organic C-rich permafrost is rapidly thawing. Recent aerial remote sensing observations over Big Trail Lake near Fairbanks, AK indicate persistent AVIRIS-NG CH_4 hotspots driven by thermokarst hydrologic dynamics [25], but no connections were made to the active beaver engineering in the area.

Beavers have constructed over 12 000 ponds in the Arctic tundra of Alaska, including a doubling between 2003 and 2017, as they colonized new regions and transformed lowland permafrost ecosystems [12, 35]. People in remote subsistence-based communities of Alaska and Canada have witnessed the influx of beavers and associated hydrologic engineering with concern due to effects on fish, water quality, and boat access [36, 37]. Beaver engineering, where prevalent, is the dominant control on increases in surface water, which is closely linked to permafrost dynamics and ecosystem processes [14]. Time-series images of beaver colonization in the Arctic tundra show that inundation and hydrologic route diversion associated with pond construction may trigger permafrost thaw and thermokarst within and surrounding the nascent wetland [12–14]. Beaver ponds alter the local thermal balance and increase heat transfer to the underlying permafrost [38, 39]. This hydrology-driven heat transfer is more effective at warming permafrost than the pre-existing vegetation cover, driving increased permafrost thaw via both lateral pond expansion and subsidence, vertical talik formation, and formation of thermokarst ponds. A case study from an ice-rich permafrost stream in western Alaska demonstrates how rapidly beaver hydrologic engineering can trigger thermo-erosional processes to thaw permafrost and restructure lowland streams [13]. Once initiated, actively thawing permafrost margins on ponds and lakes can quickly become sites of high CH_4 emissions, which can remain active for decades [40].

We explore the relationship between beaver engineering and CH_4 release in a permafrost landscape by examining spatial correlations between remotely-sensed CH_4 hotspots and beaver ponds. We compare the occurrence of CH_4 hotspots, derived from AVIRIS-NG data, in beaver-affected waterbodies and non-beaver affected waterbodies over 429.5 km^2 of an Arctic tundra region in Northwestern AK. We predicted that AVIRIS-NG CH_4 hotspots are more abundant in the terrestrial areas surrounding beaver ponds compared to terrestrial areas surrounding non-beaver affected waterbodies. Results demonstrate how this rapidly expanding new disturbance regime is altering the carbon cycle along Arctic streams.

2. Methods

2.1. Study area

We selected an area (429.5 km^2) of the lower Noatak River basin in Northwestern Alaska where six overlapping AVIRIS-NG flightlines were acquired on 24 July 2018 (figure 1). The study area includes abundant lowland wetlands, riparian wetlands, lakes, and low-order streams that drain alpine and subalpine watersheds. The study site is located in the continuous permafrost zone [41]. Mean annual air temperature is −5.06 °C and mean annual precipitation is 279.4 mm at nearby Kotzebue, AK [42].

2.2. Beaver disturbance mapping

Beaver ponds (n = 118) were identified and delineated from very high resolution cloud-free satellite imagery from June, July, and August 2019 (<1 m, GeoEye-1) using expert photo interpretation at a scale 1:2000 following previous methods [35](figure 2). Complete coverage of cloud-free imagery was unavailable for 2018. Beaver pond density is moderate in the study area compared to elsewhere in the western Alaska tundra, and the number of ponds within and nearby this study area increased from 153 to 364 between 2003 and 2017 [35].

2.3. Airborne remote sensing of CH_4 hotspots

AVIRIS-NG imagery was retrieved from the study region on 24 July 2018 [45]. These data include six overlapping flight lines with a ∼5 m spatial resolution. Identification of AVIRIS-NG CH_4 hotspots followed previously published methodology [24, 46, 47]. AVIRIS-NG CH_4 hotspots are defined as pixels with ppm m (integrated concentration path length units) CH_4 enhancement >2500 ppm m [24, 46, 47]. All enhancements above the 2500 ppm m threshold are integrated as binary detections [47]. Surface reflectance was estimated as in [48]. CH_4 bias was removed using models described in [25].

Ground measurements were conducted outside the scope of this study, at Big Trail Lake in interior Alaska. Big Trail Lake sits within Goldstream Valley, a boreal forest marsh underlain by discontinuous permafrost. Beavers are often found in a lodge on the bank of the lake, and their engineering is common in nearby Goldstream Creek, including 30 m downstream of the lake outlet. Big Trail Lake and the Goldstream Valley is a warmer version of the study area here, probably including less permafrost but ample shrubs. We acknowledge some of these differences, but we also assume that the relationships that were established between AVIRIS-NG hotspots and CH_4 emissions at Big Trail Lake apply similarly in our study area [25].

2.4. Water layer development

To compare beaver and non-beaver (control) waterbodies, we created a water layer for the study landscape (figure 2) utilizing the National Hydrography Dataset (NHD) [49] and beaver pond polygons. Flowlines and waterbodies were rasterized at ∼5 m resolution to form the basis of the water layer. Beaver pond polygons were rasterized at ∼5 m resolution from very high resolution imagery (GeoEye-1) and added to the water layer. The main channel of the Noatak river was removed from the water layer through photo interpretation and manual editing of the water layer. The water layer was manually checked for errors by visual comparison with true color AVIRIS-NG images.

To minimize the potential effects of comparing beaver waterbodies to distant non-beaver waterbodies with dissimilar environmental features and to exclude possible inadvertent inclusion of adjacent beaver waterbodies, the all water layer was refined to produce a second water layer (nearby water). For the nearby water layer, non-beaver waterbodies were defined as water pixels >100 m from beaver water pixels, <450 m from beaver water pixels, and with no apparent beaver dams, lodges, or evidence of flooding. The refinement was to provide a more direct comparison to beaver water pixels in terms of spatial proximity, geographic and ecological similarity, and total surface water area (beaver affected water area: 1623 687 m^2, non-beaver affected water area: 1600 038 m^2).

2.5. Streams and lakes

Water pixels were classified as streams or lakes through expert assessment. Streams were derived from the flowlines of the NHD and considered as flowing waterbodies including beaver ponds on flowing waterbodies. Lakes were derived from the waterbodies of the NHD and considered as non-flowing waterbodies (figure 2). Of the beaver ponds, 44 were classified as lakes and 74 were classified as streams.

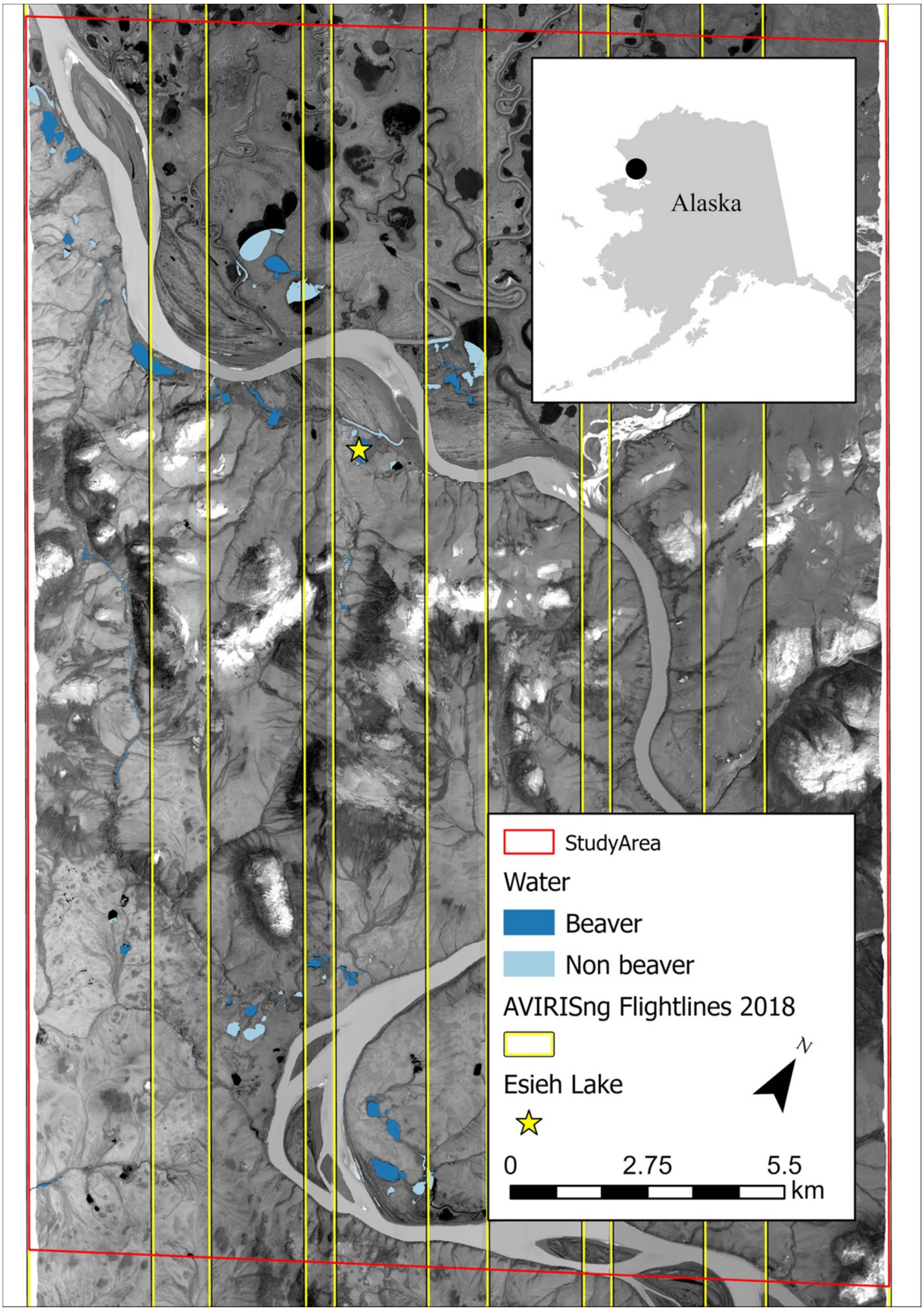

Figure 1. Study area in northwest Alaska, showing locations of 118 beaver ponds (many barely visible at this scale) and proximal non-beaver waterbodies for comparison. Imagery is from NASA AVIRIS-NG, acquired on 2018-07-24 [43]. Flightlines include ang20180724t183517, ang20180724t184947, ang20180724t190505, ang20180724t191928, ang20180724t193427, and ang20180724t194858. Esieh Lake is described in Sullivan *et al* [44].

2.6. Distance to and elevation above water

Distance to water was calculated for each pixel to use in hotspot analysis. Pixels <10 m from water were excluded from analysis to account for any mixed water or land pixel effects. Elevation above water was calculated for each non-water pixel. Elevation was obtained from the 5 m IFSAR digital elevation model [50].

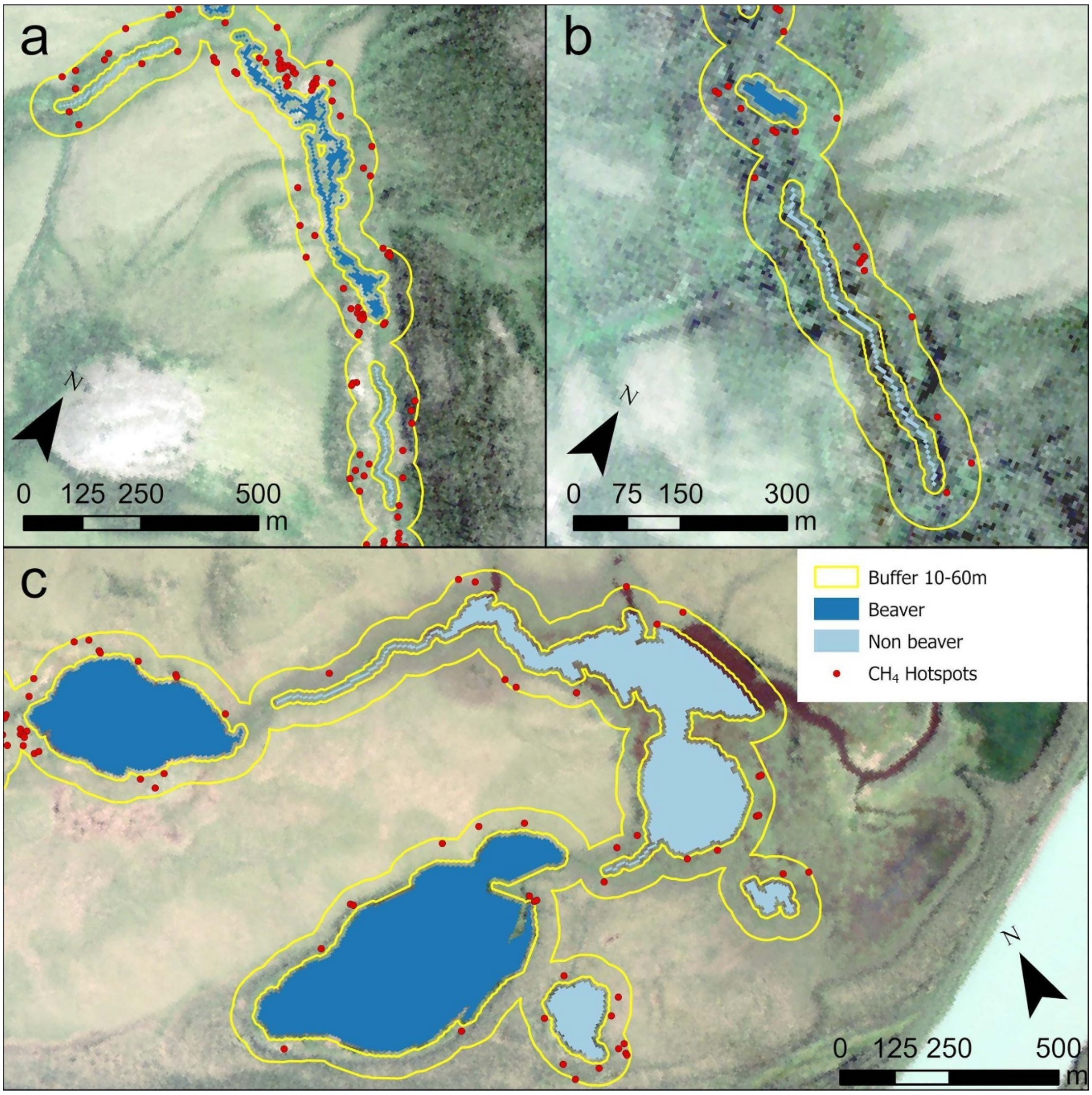

Figure 2. The spatial distribution and abundance of AVIRIS-NG CH_4 hotspots (enlarged as points for visibility) around example beaver ponds, compared to non-beaver waterbodies. (a) Stream network and analysis buffer (10–60 m) with extensive beaver pond complex of multiple dams and ponds, (b) headwater stream with small beaver pond in stream, and (c) examples of beaver and non-beaver lakes. Imagery is from NASA AVIRIS-NG, acquired on 2018-07-24 [43].

2.7. Analysis

We calculated CH_4 hotspot occurrence ratios (ratio of hotspot pixels to total pixels, CH_4HOR) for beaver pond margins and non-beaver waterbody margins [24, 47]. Water margins were defined as the area around water features out to a distance of 60 m. CH_4HOR were compared between beaver waterbodies and non-beaver waterbodies using an upper-tailed modified *z*-test [51]. We predicted that beaver CH_4HOR were greater than non-beaver CH_4HOR. Statistical tests were performed for 5 m distance bins from each water pixel.

3. Results

AVIRIS-NG CH_4 hotspots covered 0.496% of the area adjacent to waterbodies in the study. Comparing the beaver waterbodies to nearby non-beaver waterbodies, in this western Alaska study area, we find, on average, 51% greater CH_4HOR around beaver waterbodies to a distance of 25 m ($p < 0.01$, figure 3). Comparing beaver waterbodies to all non-beaver waterbodies (including waterbodies >450 m from beaver-affected water), we find significantly greater CH_4HOR around beaver waterbodies to a distance of 60 m ($p < 0.001$, figure 3). Nearby non-beaver waterbodies have a slightly elevated CH_4HOR relative to all non-beaver waterbodies to a distance of 60 m ($p < 0.01$; figure S1).

3.1. Streams and lakes

We find a strong enhancement of CH_4HOR adjacent to beaver stream segments relative to non-beaver streams to a distance of 30 m ($p < 0.05$, figure 3). However, lakes show no significant differences in CH_4HOR between beaver and non-beaver

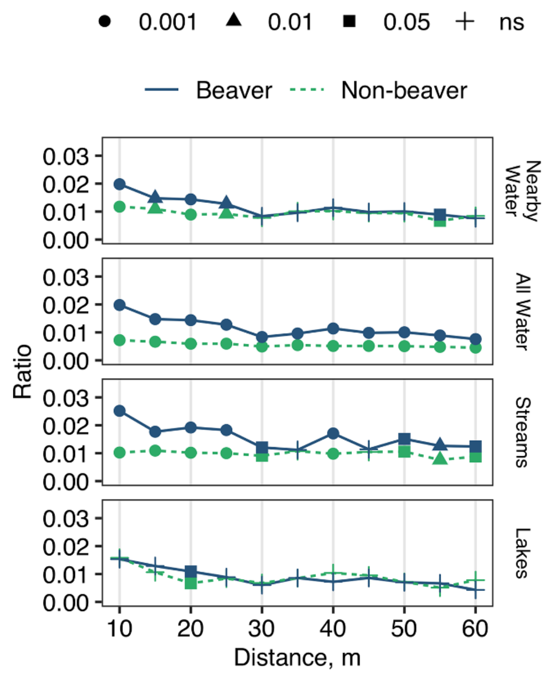

Figure 3. CH_4HOR for beaver and non-beaver water pixels with significance levels calculated at each 5 m distance. Beaver waterbodies have elevated CH_4HOR from 10 m–25 m relative to nearby waterbodies and from 10 m–30 m+ for all waterbodies and non-beaver streams. For the number of pixels analyzed for each group see table S1.

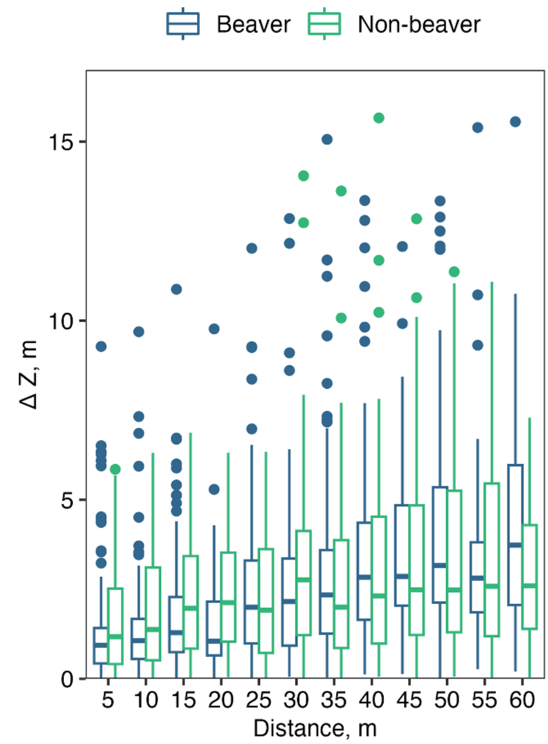

Figure 4. Boxplots of elevation of AVIRIS-NG CH_4 hotspots above waterbodies (ΔZ) at each distance bin. The boxplot middle line represents the median, the hinges are the first and third quartiles, the whiskers are 1.5× the interquartile range, and the points are values outside of the whisker range.

lakes at most distances (figure 3). Beaver streams show greater CH_4HOR (10–30 m) compared to beaver lakes ($p < 0.05$, figure S2). Non-beaver streams and lakes show no consistent difference in CH_4HOR.

3.2. Elevation above water

The elevation of hotspots relative to the elevation above the nearest waterbody (ΔZ) was calculated to understand the potential influence of flooding and raised water tables on AVIRIS-NG CH4 hotspots. A majority of AVIRIS-NG CH_4 hotspots occur at <3 m above nearby waterbodies to 30 m distance (figure 4).

3.3. Hotspot spatial decay ratio

We calculated the power law fits for the beaver and non-beaver CH_4HOR (figure 5). The power law fit for 10–35 m shows strong exponential decay with distance for both beaver and non-beaver hotspots ($R^2 = 0.87$, 0.85). The decay rate of the power law fit (10–35 m) for the ABoVE domain (Northwestern Canada and Alaska) is very close to that of the decay rate of the beaver fit (−0.649 vs −0.6254). Beyond 40 m, CH_4HOR declined gradually (figure 5). Overall, we see an enhancement of CH_4HOR in this study landscape compared to the ABoVE domain-wide average [24]. The non-beaver CH_4HOR are ∼50% greater while the beaver CH_4HOR are ∼400% greater than those for the entire ABoVE domain.

4. Discussion

Detecting CH_4 efflux at landscape and regional scales using hyperspectral imaging and spectroscopy is a relatively new technique that has not been applied to test the effects of beaver ponds. This study provides evidence relating AVIRIS-NG hotspots, shown to represent high CH_4 efflux in a similar boreal forest setting, to beaver ponds on a landscape scale. Specifically, we used airborne imaging spectroscopy surrounding 118 beaver pond locations over an area of 429.5 km^2 and found that beaver ponds in the Arctic enhance AVIRIS-NG hotspots from adjacent terrestrial surfaces. We interpret the increased hotspots surrounding beaver ponds as being indicative of increased CH_4 emissions, likely due to a combination of wetland formation and permafrost thaw. New beaver damming and construction of ponds along Arctic streams, including a doubling of beaver ponds in the Alaskan Arctic from 2003–2017 [35], is thus increasing CH_4 emissions from adjacent terrestrial surfaces and amplifying the warming already underway. Future work should include ground measurements of methane flux and a better understanding of the processes driving methane production and release surrounding tundra beaver ponds.

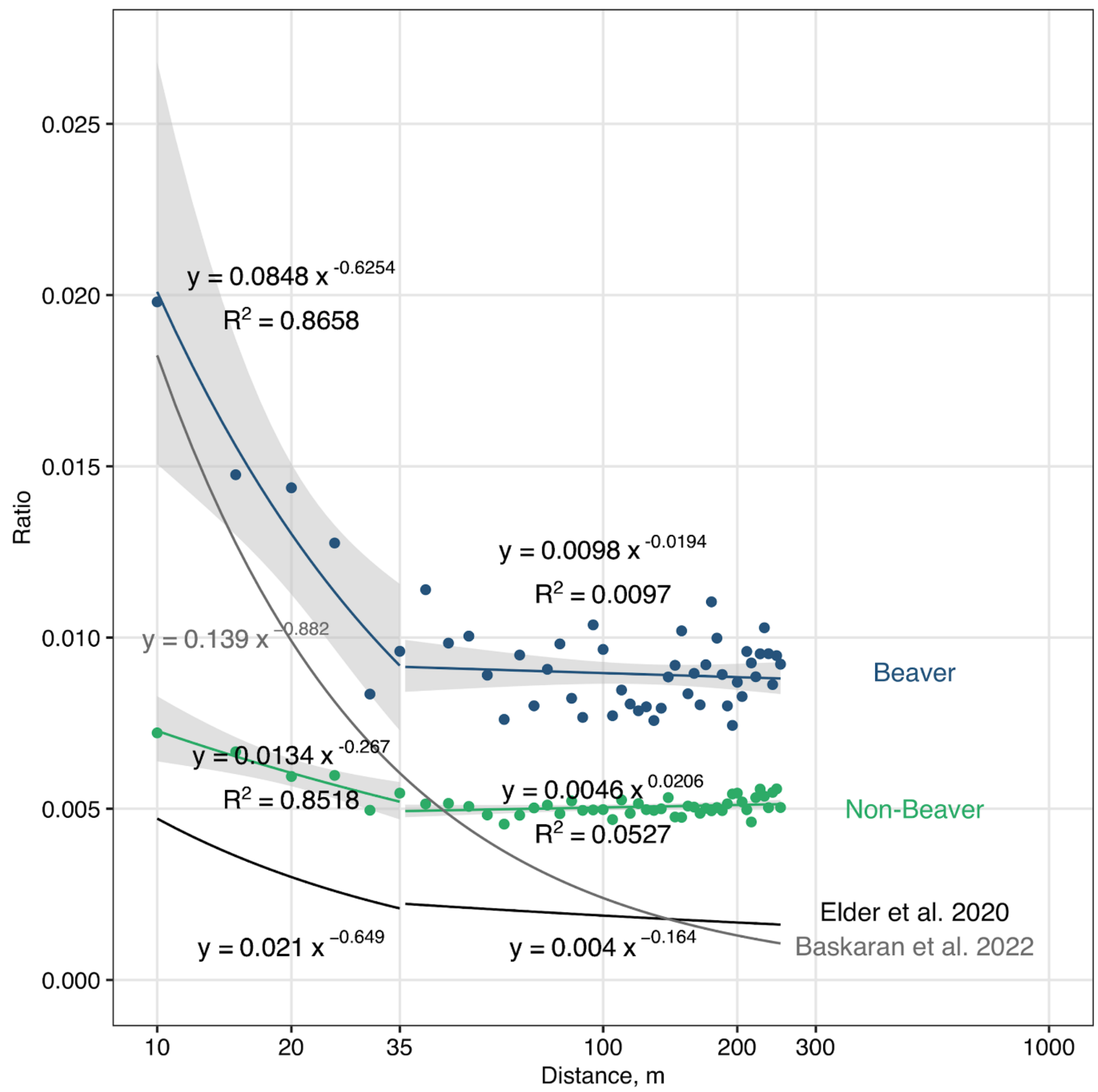

Figure 5. Power law fits for CH_4HOR for beaver and all non-beaver water pixels. Power law functions and R^2 are presented in the figure for beaver (blue), non-beaver (green) water pixels for 10–35 m and 40–250 m distance from water. Power law functions from [24] in black and from [47] in gray.

4.1. Beaver engineering and CH_4 in non-permafrost ecosystems

Beaver engineering shifts streams from free-flowing to standing water systems. If beavers persist in an area, they create dynamic landscape mosaics that transition over time between free-flowing streams, impounded water in ponds, and wetlands [52]. Beaver engineering increases the width of the riparian zone and the length of riparian and upland interface, creating ponds and wetlands [53], which promote anoxic conditions and CH_4 production through methanogenesis [30, 31]. The evolving and complex nature of beaver engineered ecosystems, however, makes it difficult to generalize spatially and temporally about the effects on the carbon cycle (of which CH_4 is only one component). Nummi *et al* [34] estimate that beaver ponds globally range from a C sink (-0.47 Tg yr^{-1}) to a C source (0.82 Tg yr^{-1}). Whitfield *et al* [26] estimated that the resurgence and introduction of beavers since 1900 accounted for emission of 0.18–0.80 Tg CH_4 yr^{-1} in 2000, a 200-fold increase from unengineered streams in 1900. A study from the boreal forest of Quebec found that beaver ponds were responsible for emitting 18% of the total CH_4 flux [54]. The high uncertainty on existing estimates of beaver pond CH_4 fluxes is partly due to the difficulty of monitoring CH_4 fluxes *in-situ* or remotely and the challenges of extrapolating spatially and temporally limited samples. Our results indicate that in the Arctic tundra environment, where permafrost predominates, beaver ponds enhance CH_4 release.

4.2. Comparison to other Arctic CH_4 hotspot studies

In this study, CH_4HOR declines exponentially with distance up to 35 m from standing water whereas at distances >35 m the decay ratio is more than an order of magnitude slower (−0.02, figure 5). The rapid decay for distances <35 m from standing water is consistent with previous CH_4 hotspot work [25, 47], and is likely due in part to topography near waterbodies, which reduces the potential for wetlands and CH_4 production beyond 35 m. The majority of beaver ponds in the study landscape occur along streams in valleys with greater slope than the few beaver ponds surrounded by relatively flat topography. The relatively higher CH_4HOR found in the Noatak landscape could be explained by thawing of permafrost with higher ground ice content, greater permafrost C stocks, younger beaver ponds, or greater general methanogenic activity compared to the ABoVE domain in aggregate [45]. Our findings are similar to those from the uplands of the Mackenzie Delta, Canada, where the non-beaver CH_4HOR are slightly lower (∼0.005–0.008), and the beaver CH_4HOR are slightly higher (∼0.009–0.02) for 10–35 m (∼0.007–0.015) [47].

4.3. CH_4 hotspots and beaver ponds in the Arctic

High CH_4 flux rates (1000–24 000 mg CH_4 $m^{-2}d^{-1}$) have been linked to hotspots identified by AVIRIS-NG using *in-situ* measurements to validate hotspots [25]. Thermokarst lakes are known to have large CH_4 fluxes to the atmosphere [55, 56]. At a thermokarst lake in central Alaska, elevated CH_4 flux measurements have been associated with thawing permafrost [57], though beaver engineering at the lake outlet and elsewhere on the adjacent stream system was not mentioned. Beaver engineering and the creation of interconnected wetlands is known to induce a cascade of environmental changes that are likely to promote CH_4 emissions. These effects are likely enhanced in the permafrost domain, where thermal effects of inundation are especially consequential for thawing permafrost C [58]. By constructing ponds along streams in permafrost, beavers are essentially emplacing thermokarst ponds along streams. Though we have associated increased AVIRIS-NG CH_4 hotspots with beaver ponds and wetlands, we cannot quantify the relative contributions of CH_4 production around nascent beaver ponds compared to CH_4 released from thawed permafrost adjacent to ponds.

The 51% increase of AVIRIS-NG CH_4 hotspots surrounding beaver ponds presented here is substantial. In this study area, beaver engineering was minimal prior to 2000, and by 2020 the density of ponds was about half of the more favorable areas to the south and east [35]. Strong increases in beaver engineering, which have occurred recently and are expected to continue, would extend the 51% local increase around beaver ponds to entire stream lengths, and possibly even across landscapes where lowland streams and beaver habitat are prevalent. The size of CH_4 emissions in the tundra due to beaver engineering depends heavily on how quickly they disperse to new areas and how favorable the habitat is in these regions. The damming of streams and the conversion of relatively small flowing waterbodies to wetland complexes could be the dominant mode of abrupt permafrost thaw (in ice-rich permafrost) and C release in young beaver-dominated stream systems undergoing colonization. The landscape response to beaver ponding varies according to the setting on a stream, slough, or lake outlet.

Beaver impacts to permafrost are most evident at the surface where active layer thickness is relatively shallow (e.g [13]), reflecting cold soil thermal conditions. In these locations, beaver engineering and expansion of surface water over near-surface permafrost leads to enhanced heat transfer into the underlying permafrost, leading to thermokarst in ice-rich terrain, and high potential for thaw and C release [13]. The presence of groundwater flow paths through gravel bars and floodplain soils likely reduces permafrost presence in braided river corridors prior to beaver arrival. Upon colonization by beavers, we expect that dams and ponds in these riverine settings (side-channels or sloughs) will have a less-pronounced effect on permafrost. However, lateral expansion of the pond over time may still function to thaw permafrost in adjacent riparian or upland soils.

In pre-existing lakes, beaver dams at the outlets typically have a reduced influence on water level, surface water extent, and lakeshore geometry. Because new terrestrial surfaces are usually minimally inundated in these situations, permafrost thaw is less common. This is consistent with our results showing that beaver dams at lake outlets are not correlated with increased AVIRIS-NG CH_4 hotspots. Where beavers dam outlets of drained thaw lake basins (e.g [14]), or where dammed outlets lead to catastrophic drainage, we expect to find permafrost thaw and CH_4 hotspots, but the study landscape contained no obvious examples of this. Beaver preference for damming drained thermokarst lakes and related landforms would contribute to enhanced CH_4 hotspot occurrence since these landscapes are rich in soil organic carbon and their inundation would be expected to promote significant methanogenesis.

4.4. Detecting CH_4 hotspots

Since the CH_4 survey excluded open water areas due to limitations of the hyperspectral imaging, potentially large ebullitive fluxes from pond sediments, thawing permafrost underneath ponds, and wetlands went undetected. However, some evidence suggests that if ebullition is prevalent within a few meters of terrestrial shorelines, and if wind conditions are favorable, this water-borne emission could supplement CH_4 enhancements over the nearby land surface where SWIR reflectances would allow CH_4 detection [25]. Even in this scenario, we are confident that the AVIRIS-NG adequately identified sites of intense CH_4 emission across our 429.5 km^2 study area and did not bias detections between beaver-affected and non-affected locations. If anything, AVIRIS-NG's capability to only observe areas of relatively extreme CH_4 provides a robustness and conservatism to our results.

Quantifying the source of CH_4 (i.e. contemporary carbon, ancient permafrost carbon, and/or geologic carbon) emitted at our observed hotspots was outside the scope of this study. However, it is worth noting that geologic emissions may influence a small number of our observations, especially near Esieh Lake where a large geologic CH_4 seep has recently been discovered [44]. To our knowledge, the primary Esieh Lake seep is located within the lake body itself, making its detection by AVIRIS-NG challenging. This is because without glint, water surfaces do not reflect enough short-wave infrared photons to perform confident CH_4 retrievals. A small number (1–3) of hotspots were observed near the shorelines of Esieh Lake and may be related to the geologic seep either directly or due to dispersal of the seep's plume over the reflective land surface. While differentiating CH_4 sources of detected hotspots was outside the scope of our study, we conclude that beavers have a significant effect on their occurrence.

Further study is warranted to both investigate the direct mechanisms that link beaver activity to increases in AVIRIS-NG CH_4 hotspots in permafrost environments and estimate actual CH_4 emission ratios as a result of beaver activity. Our approach of only considering nearby water pixels for analysis is more conservative than including all water pixels, as demonstrated by the rapid decline and lower significance of hotspots nearby water compared to all water (figure 3). Moreover the use of only nearby water pixels and the exclusion zone (0–10 m) creates a conservative approach to detecting AVIRIS-NG CH_4 hotspots. There are likely many hotspots near water (distance $<$10 m) that are being excluded that could have been included and likely have elevated CH_4 fluxes due to their proximity to water. A more accurate and higher resolution water mask could help to refine this process and lead to better detection of AVIRIS-NG CH_4 hotspots at the margins of waterbodies, but the resolution of AVIRIS-NG may still be limiting.

Finally, it is conceivable, though unlikely, that beavers are targeting pre-existing CH_4 hotspots to construct their ponds, in which case beaver pond construction would not be responsible for the correlated hotspots. If we assume that beavers are not targeting CH_4 hotspots to construct their ponds, then the increases in AVIRIS-NG CH_4 hotspots are attributable to beaver pond construction and the associated changes to permafrost and lowland ecosystems. We believe the evidence presented here makes a strong case for this latter scenario where beaver engineering is causing the associated changes in permafrost and CH_4 emissions. Future work will exploit time series imagery, imagery along a gradient of permafrost coverage, and ground based gas flux measurements to resolve this issue definitively.

5. Conclusion

As the Arctic warms, local-scale changes have the potential to amplify large-scale climate forcings causing cascading effects to landscapes and ecosystems. As beavers proliferate and spread into new tundra areas, they actively flood and inundate permafrost terrain, driving increases in CH_4 release through permafrost thaw and thermokarst processes. This study is the first attempt to link large numbers of new beaver ponds to CH_4 emissions at the landscape scale, and these results suggest that beaver engineering in the Arctic will at least initially increase CH_4 release.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.3334/ORNLDAAC/1569 [43].

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