Cumulative impacts of a gravel road and climate change to vegetation in an ice-wedge polygon landscape, Prudhoe Bay, Alaska

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Figure 1. Roadside area through a network of ice-wedge polygons, Prudhoe Bay Oilfield, Alaska. The effects of roadside flooding and road dust have caused subsidence of the ice-wedges and erosion of the polygon centers, transformed the previous low-centered polygons to high-centered polygons, and altered the soil properties and vegetation of the polygon centers and troughs in a wide swath of tundra adjacent to the road.

Introduction

Environmental impact assessments for new infrastructure in Arctic–tundra areas with ice-rich permafrost do not adequately consider the likely long-term cumulative effects of climate change and proposed infrastructure (Raynolds et al. 2014). This is due in part to the lack of historical case studies that document long-term changes. Here, we present a vegetation analysis that supports a case study that examined the long-term (1949–2020) changes in a network of low-centered ice-wedge polygons along a heavily traveled road, in the Prudhoe Bay Oilfield (PBO), AK (Walker et al. 2021).

Aim

Our goal was to determine how present-day plant community structure and composition adjacent to a heavily traveled gravel road in the PBO compares with vegetation in similar undisturbed habitats sampled in the 1970s. We examined scenarios of change in areas with increasingly severe cumulative impacts caused by climate change, road dust, and road-related flooding.

Methods

Location

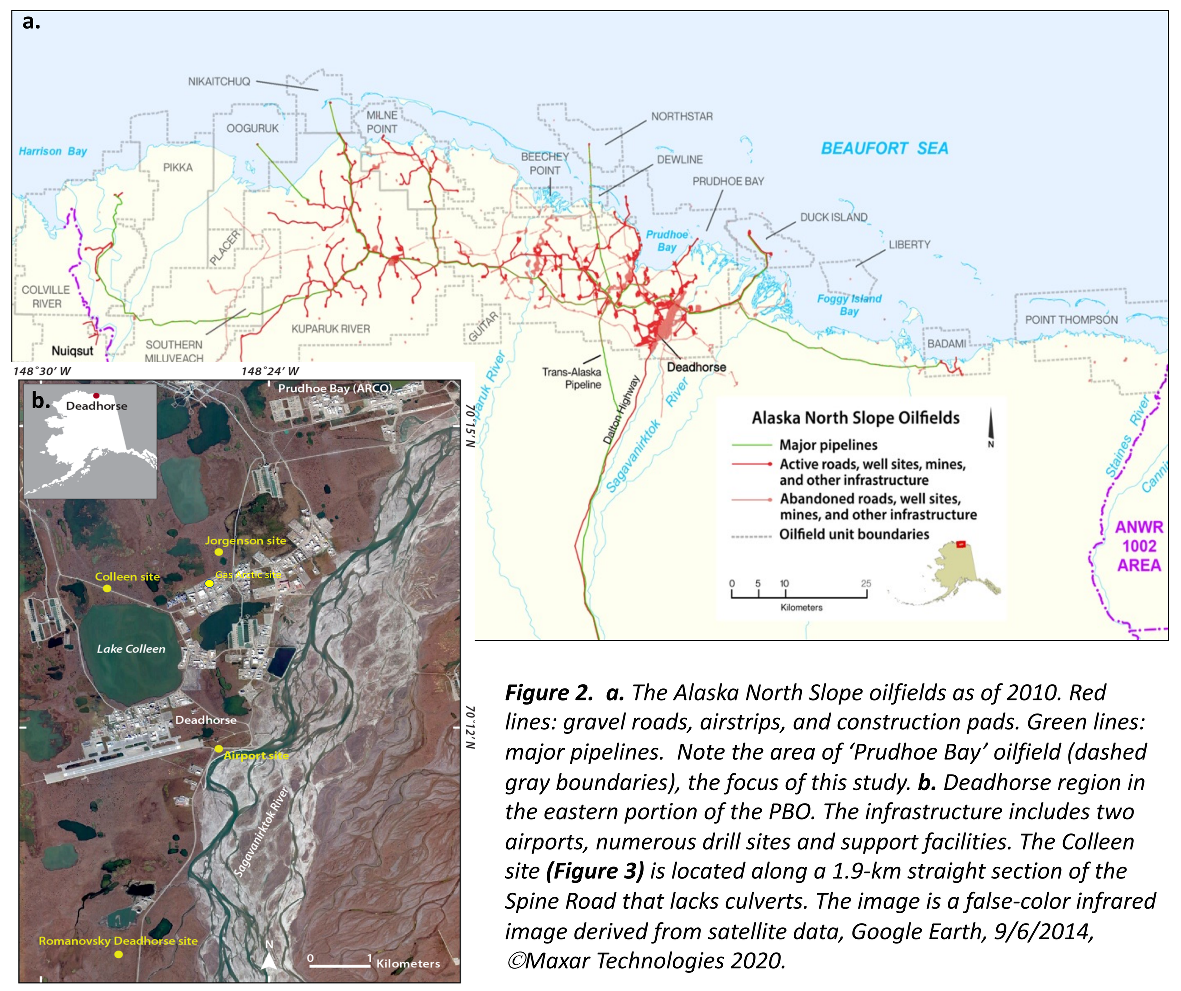

Figure 2. **a.** The Alaska North Slope oilfields as of 2010. Red lines: gravel roads, airstrips, and construction pads. Green lines: major pipelines. Note the area of 'Prudhoe Bay' oilfield (dashed gray boundaries), the focus of this study. **b.** Deadhorse region in the eastern portion of the PBO. The infrastructure includes two airports, numerous drill sites and support facilities. The Colleen site (**Figure 3**) is located along a 1.9-km straight section of the Spine Road that lacks culverts. The image is a false-color infrared image derived from satellite data, Google Earth, 9/6/2014, ©Maxar Technologies 2020.

Colleen site transects and plots

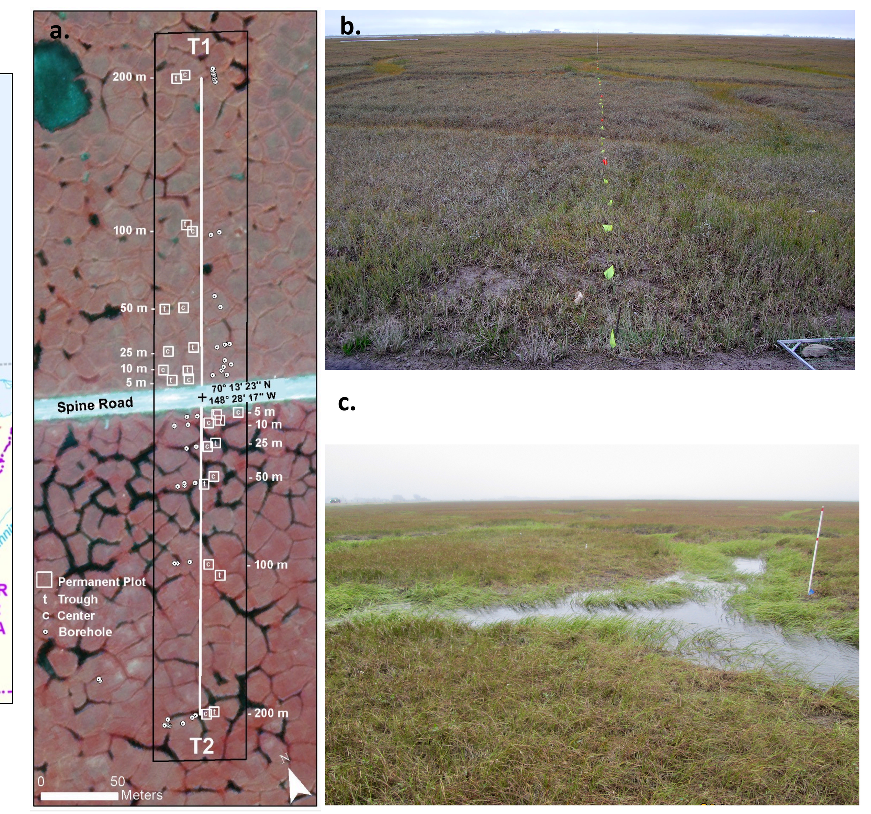

Figure 3. The Colleen site (CS). **a.** Digital false-color infrared aerial photograph (9 Aug 2010). Note the 200-m transects (white lines) T1 (NE side of the road) and T2 (SW side), and the paired vegetation plots (open white squares) in polygon troughs (t) and polygon centers (c) at approximately 5, 10, 25, 50, 100, and 200 m from both sides of the road. **b.** Ground view of Transect T1 on the relatively well-drained NE side of the road. Heavy road dust is apparent on this side of the road. **c.** Transect T2 on the flooded SW side of the road, where the troughs between ice-wedge polygons are eroded and filled with water.

Plot sampling

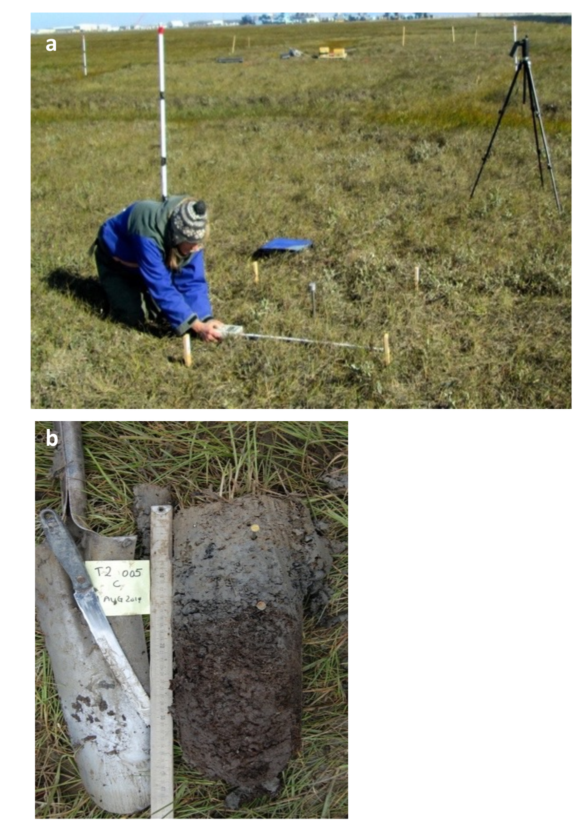

Figure 4. Sample plot. **a.** 24 1-m x 1-m plots were located along Transects 1 and 2 in representative ice-wedge polygon centers and troughs. **b.** Soil plug from an area adjacent to the plot. . **Note:** The 14-cm thick mineral surface horizon, is the dust layer that has collected during 46 years since road construction in 1969.

Scenarios of change

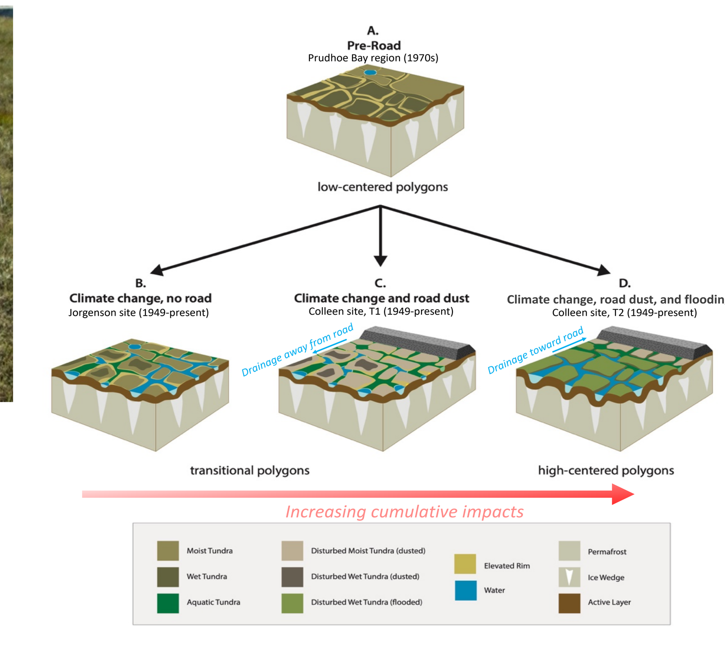

Figure 5. Scenarios of change. **Scenario A:** Prior to road construction (1949–1968); analysis used historical aerial photographs and literature sources from before and shortly after the Spine Road was constructed in 1969. **Scenario B:** Climate change, no road; analysis focused mainly on the Jorgenson Site (JS), which is a nearby previously studied site that is relatively isolated from road-related effects. **Scenario C:** Climate change and road dust; analysis focused on the northeast, non-flooded side of the road. **Scenario D:** Climate change, road dust, and flooding: Analysis focused on the southwest, flooded, side of the road.

Data analysis

Data sources

Two vegetation datasets were selected from the Alaska Arctic Vegetation Archive (AVA-AK, https://arcticatlas.geobotany.org/catalog/group/plot-archive) for the analyses:

- Walker (1985) for the 23 Prudhoe Bay plots sampled in 1975–1976
- Walker et al. (2015) for the 26 CS plots sampled in 2014

The analysis 11 environmental variables that were common to both datasets, and 120 species. The vegetation data management software TURBOVEG (Hennekens and Schaminée 2001) was used to store, select, and import vegetation data for analysis.

Cluster analysis

Cluster analysis was used to group plots with similar plant species composition into recognizable vegetation types. The defined groups were also used for the synoptic table and the ordination. An agglomerative dendrogram approach using the flexible beta group linkage method and Sørensen's distance measure, available in the PC-Ord package for multivariate analysis of ecological data (McCune et al. 2002), was selected to hierarchically arrange the vegetation plots into clusters.

Synoptic table

A synoptic table was used to examine the species composition of each cluster and to identify species with high fidelity (diagnostic species), high constancy (frequent species), and high mean cover (dominant species). The table was constructed using the JUICE program for analysis and classification of vegetation data (Tichý, 2002).

Species analyses

The synoptic table helped identify **diagnostic species** that were present in each cluster of undisturbed (1970s) plots but missing in comparable disturbed (2014) plots. **Species richness** of the disturbed moist, wet, and aquatic vegetation types were compared in 2014 and 1970s datasets. **Growth-form cover** of the moist and wet types were compared for the Prudhoe (1970s) and Colleen (2014) datasets.

Environmental analyses

The ordination provided a visual summary of plots in relationship to the complex natural and anthropogenic gradients. We used the non-metric multidimensional scaling (NMDS) ordination approach with the Sørensen distance measure (Kruskal 1964) available in the PC-Ord® software package for analysis of ecological communities (McCune et al. 2002).

Results

Cluster analysis

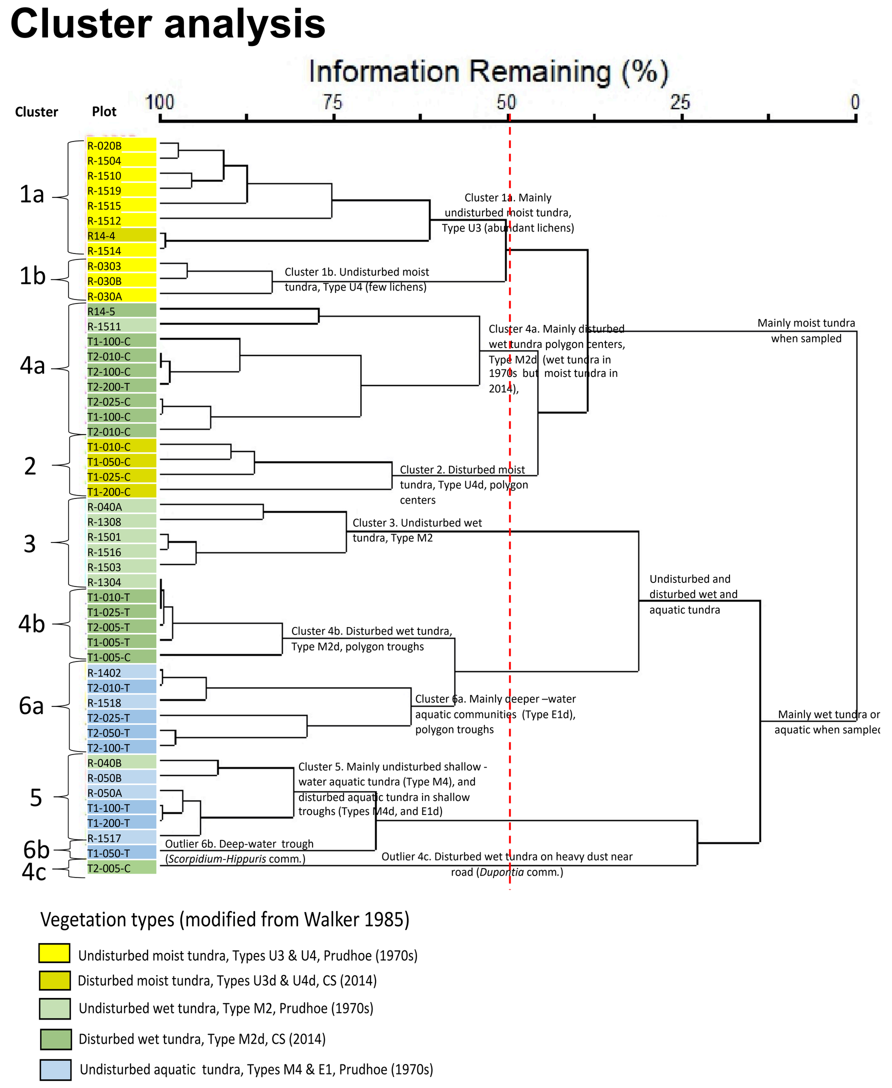

Figure 6. Cluster analysis of CS (2014) and Prudhoe (1970s) plots. Brief descriptions of the numbered clusters are on the branches of the dendrogram.

Synoptic table

Table 1. *Synoptic table of fidelity (Φ), frequency (%), and mean cover (%) of diagnostic taxa in plots of undisturbed moist, wet, and aquatic tundra plant communities sampled during the 1970s (Walker et al. 1980) and plots affected by road-related disturbances at the Colleen site sampled in 2014. Highly diagnostic taxa (Φ ≥ 50) are highlighted dark gray; diagnostic taxa (35 ≤ Φ < 50) are highlighted light gray.*

Group		1			2			3			4			5			6			7			8		
Cluster		1a			1b			2			3			4a			4b			5			6a		
Description		Undisturbed moist tundra (1970s), Type U3			Undisturbed moist tundra (1970s), Type U4			Disturbed moist tundra (2014), Types U3d & U4d			Undisturbed wet tundra (1970s), Type M2			Mainly disturbed tudra (2014), Type M2d, heavily dusted and flooded centers of T2			Mainly disturbed tudra (2014), Type M2d, polygon troughs of T1			Mainly shallow-water aquatic tundra, Types M4, M4d, E1, E1d (1970s & 2014)			Mainly deeper water aquatic tundra, types M4d, E1d (2014)		
Nr. plots		8			3			4			5			9			6			6			6		
Taxa	Growth form	Φ	Freq.	Mean cover	Φ	Freq.	Mean cover	Φ	Freq.	Mean cover	Φ	Freq.	Mean cover	Φ	Freq.	Mean cover	Φ	Freq.	Mean cover	Φ	Freq.	Mean cover	Φ	Freq.	Mean cover
Diagnostic taxa																									
Group 1, undisturbed moist tundra, Type U3																									
Lecanora epibryon (Ach.) Ach.	crustose lichen	85	75	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0
Pedicularis lanata Willd. ex Cham. & Schltdl.	erect forb	85	75	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0
Tephroseris frigida (Richardson) Holub	erect forb	78	75	0	---	0	0	---	0	0	---	0	0	---	11	0	---	0	0	---	0	0	---	0	0
Hulteniella integrifolia (Richardson) Tzvelev	erect forb	77	63	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0
Thamnolia vermicularis s. subuliformis (Sw.) Schae	fruticose lichen	69	88	3.4	---	33	0	---	0	0	---	20	0	---	0	0	---	0	0	---	0	0	---	0	0
Flavocetraria cucullata (Bell.) Kärnefelt & Thell	fruticose lichen	68	50	0.1	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0
Hypnum bambergeri Schimp.	pleurocarpous moss	68	88	3.8	---	33	2	---	25	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0
Hypnum procerrimum Molendo	pleurocarpous moss	59	38	2	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0
Arctagrostis latifolia (R. Br.) Griseb.	rhizomatous grass	59	38	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0
Draba alpina L.	rosette forb	59	38	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0
Papaver macounii Greene	erect forb	59	38	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0
Salix rotundifolia v. *rotundifolia* Trautv.	deciduous prostrate dwarf shrub	59	38	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0
Dactylina arctica (Richardson) Nyl.	fruticose lichen	57	75	0.6	---	67	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0
Saxifraga oppositifolia s. *oppositifolia* L.	cushion forb	53	88	0.5	---	0	0	---	50	0	---	60	0	---	11	0	---	0	0	---	0	0	---	0	0
Carex membranacea Hook.	rhizomatous sedge	50	88	8.1	---	33	0	---	50	1	---	40	0.7	---	11	1	---	0	0	---	0	0	---	0	0
Oncophorus wahlenbergii Brid.	pleurocarpous moss	49	50	0.1	---	33	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0
Sanionia uncinata (Hedw.) Loeske	pleurocarpous moss	48	25	3	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0
Cassiope tetragona [s. *tetragona*] (L.) D. Don	evergreen dwarf shrub	48	25	0.3	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0
Abietinella abietina (Hedw.) Fleisch.	pleurocarpous moss	48	25	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0
Cardamine digitata Richardson	erect forb	48	25	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0
Carex scirpoidea Michx.	rhizomatous sedge	48	25	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0
Didymodon asperifolius (Mitt.) H. Crum, Steere & L	acrocarpous moss	48	25	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0
Masonhalea richardsonii (Hook.) Kärnefelt	fruticose lichen	48	25	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0
Minuartia arctica (Steven ex Ser.) Graebn.	mat forb	48	25	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0
Encalypta species	acrocarpous moss	46	38	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	17	0	---	0	0
Solorina species	foliose lichen	45	50	0.1	---	33	0	---	0	0	---	0	0	---	11	0	---	0	0	---	0	0	---	0	0
Meesia uliginosa Hedw.	acrocarpous moss	43	75	0	---	67	0.7	---	0	0	---	60	0.8	---	0	0	---	0	0	---	0	0	---	0	0
Cetraria islandica (L.) Ach.	fruticose lichen	43	63	0.7	---	67	0.7	---	0	0	---	20	0	---	0	0	---	0	0	---	0	0	---	0	0
Tomentypnum nitens (Hedw.) Loeske	pleurocarpous moss	40	100	13.9	---	100	9.3	---	75	1.5	---	40	0.3	---	44	1.8	---	17	0	---	0	0	---	0	0
Peltigera canina (L.) Willd.	foliose lichen	38	38	0	---	33	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0
Groups 1 & 2, undisturbed moist tundra, Types U3 and U4																									
Ditrichum flexicaule (Schwaegr.) Hampe	acrocarpous moss	50	100	18.3	50	100	2	---	25	3	---	40	0	---	11	0	---	17	3	---	0	0	---	0	0
Salix reticulata L.	deciduous prostrate dwarf shrub	40	88	2.7	50	100	4.3	---	25	3	---	60	0	---	22	5.3	---	0	0	---	0	0	---	0	0
Groups 1 & 3, undisturbed and disturbed moist tundra																									
Dryas integrifolia s. *integrifolia* Vahl	evergreen prostrate dwarf shrub	37	100	16.5	---	100	15.3	37	100	3.2	---	60	0	---	44	3.2	---	0	0	---	0	0	---	0	0
Carex bigelowii Torr.	rhizomatous sedge	35	63	5.5	---	33	2	46	75	0	---	0	0	---	0	0	---	17	0	---	0	0	---	0	0
Group 2, undisturbed moist tundra, Type U4																									
Plagiochila arctica Bryhn & Kaal.	leafy liverwort	---	25	0	66	67	1.3	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0
Blepharostoma trichophyllum v. *brevirete* Bryhn & K	leafy liverwort	---	13	0	66	67	0	---	0	0	---	0	0	---	11	0	---	0	0	---	0	0	---	0	0
Timmia austriaca Hedw.	acrocarpous moss	---	13	0	62	67	0	---	0	0	---	20	0	---	0	0	---	0	0	---	0	0	---	0	0
Cratoneuron filicinum (Hedw.) Spruce	pleurocarpous moss	---	38	0	60	67	0.7	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0
Cinclidium arcticum Schimp.	acrocarpous moss	---	13	0	50	67	2	---	0	0	---	40	6	---	0	0	---	0	0	---	17	0	---	0	0
Carex maritima Dewey	caespitose sedge	---	13	1	50	67	0	---	0	0	---	40	0.7	---	0	0	---	0	0	---	17	0	---	0	0
Pedicularis albolabiata (Hultén) Kozhevn.	erect forb	---	0	0	43	100	0	---	75	0	---	80	0.3	---	44	0	---	0	0	---	50	0.8	---	0	0
Groups 2 & 4, undisturbed moist tundra, Type U4, and undisturbed wet tunda, Type M2																									
Orthothecium chryseum (Schwaegr.) B.S.G.	pleurocarpous moss	---	63	2.9	57	100	2.3	---	0	0	41	80	1.2	---	0	0	---	0	0	---	0	0	---	0	0
Calliergon megalophyllum Mikutowicz	pleurocarpous moss	---	38	0.5	53	100	0.2	---	0	0	53	100	4.2	---	0	0	---	17	0	---	17	5	---	0	0
Campylium stellatum (Hedw.) C. Jens.	pleurocarpous moss	---	63	1.6	50	100	9.7	---	0	0	50	100	2.4	---	11	0	---	0	0	---	17	3	---	0	0
Group 3, disturbed moist tundra																									
Braya glabella s. *purpurascens* (R. Br.) Cody	rosette forb	---	0	0	---	0	0	73	75	0	---	0	0	---	22	0	---	0	0	---	0	0	---	0	0
Tortella tortuosa (Hedw.) Limpr.	acrocarpous moss	---	13	0	---	67	0.7	50	75	0.6	---	0	0	---	0	0	---	17	0	---	0	0	---	0	0
Salix richardsonii Hook.	deciduous erect dwarf shrub	---	38	3.2	---	100	2.3	39	100	12.8	---	60	0	---	78	7.4	---	17	0	---	0	0	---	0	0
Gouprs 3 & 4, disturbed moist and undisturbed wet tundra																									
Drepanocladus brevifolius (Lindb.) Warnst.	pleurocarpous moss	---	63	6.4	---	100	12.7	34	100	9.5	34	100	39.2	---	44	12.5	---	17	0	---	17	2	---	0	0
Group 4, undisturbed wet tundra																									
Cinclidium latifolium Lindb.	acrocarpous moss	---	25	0.3	---	33	0	---	0	0	69	100	6.3	---	11	1	---	0	0	---	17	0	---	0	0
Salix ovalifolia v. *ovalifolia* Trautv.	deciduous prostrate dwarf shrub	---	13	1	---	0	0	---	50	9.5	68	100	1.3	---	11	3	---	17	16	---	0	0	---	0	0
Dupontia fisheri R. Br.	rhizomatous grass	---	13	0	---	33	0	---	0	0	68	100	0.1	---	11	0	---	33	0	---	0	0	---	0	0
Carex saxatilis s. *laxa* (Trautv.) Kalela	rhizomatous sedge	---	0	0	---	0	0	---	0	0	57	60	0.5	---	0	0	---	0	0	---	33	2	---	0	0
Juncus biglumis L.	rush	---	13	0	---	33	0	---	0	0	45	60	0	---	22	0	---	0	0	---	0	0	---	0	0
Meesia triquetra (H. Richter) Aongstr.	acrocarpous moss	---	13	0	---	0	0	---	0	0	41	60	9.7	---	22	1	---	33	1	---	17	0	---	0	0
Bistorta vivipara (L.) Delarbre	erect forb	---	63	0	---	100	0	---	100	0.4	33	100	0	---	56	0	---	33	0	---	0	0	---	0	0
Group 7, shallow-water aquatic tundra																									
Scorpidium scorpioides / Limprichtia revolvens	pleurocarpous moss	---	0	0	---	33	0	---	0	0	---	40	5.5	---	11	16	---	50	0.6	51	100	26.8	---	50	8
Group 8, deep-water aquatic tundra																									
Calliergon giganteum (Schimp.) Kindb.	pleurocarpous moss	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	0	0	---	17	16	57	50	23.3

Species analyses

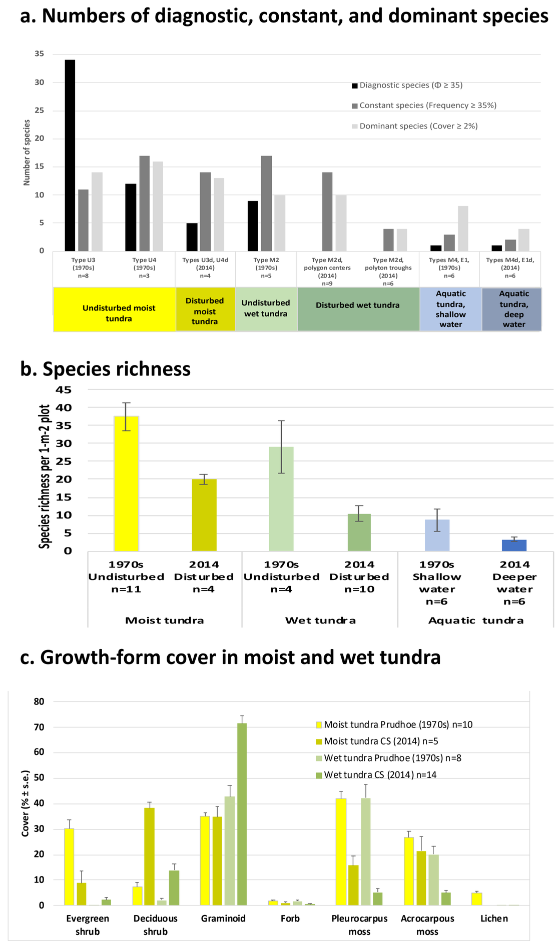

Figure 7. *Comparison of the Prudhoe (1970s, undisturbed) and Colleen (CS 2014, disturbed) tundra datasets.* ***a.*** *Numbers of diagnostic, constant, and dominant species. Derived from the synoptic table (**Table 1**).* ***b.*** *Species richness in moist, wet, and aquatic undisturbed and disturbed vegetation units derived from the cluster analysis (**Figure 6**) [mean ± standard error of the mean (s.e.).* ***c.*** *Growth-form cover in groups of moist and wet undisturbed and disturbed plots.*

Environmental analysis

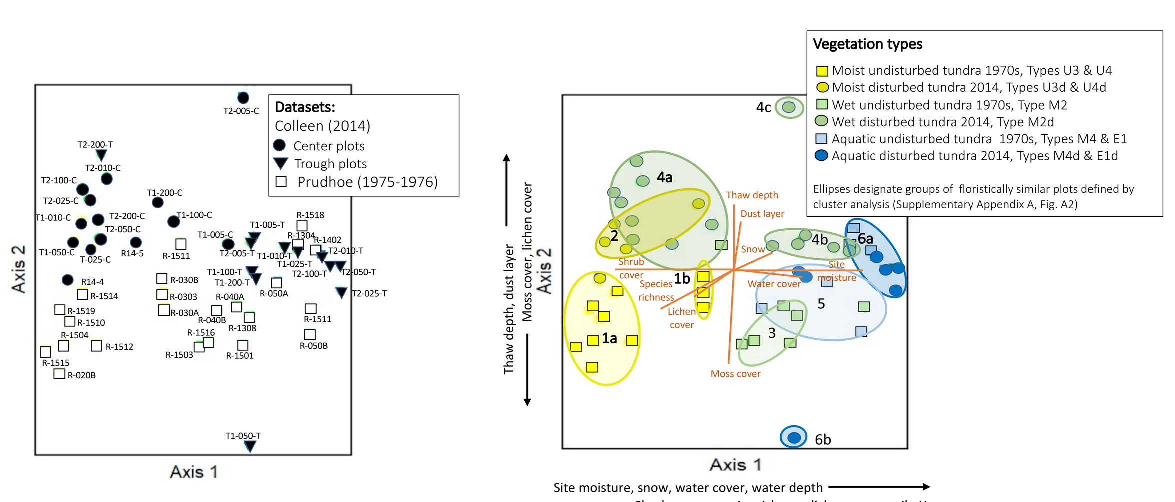

Figure 8. Ordination of the disturbed CS (2014) and comparable undisturbed Prudhoe (1970s) plots. **a.** NMDS ordination of plots showing the distribution of undisturbed (1970s) plots (open squares), disturbed (2014) polygon-center plots (closed circles) and disturbed (2014) polygon-trough plots (closed inverted triangles). Labels are plot ID numbers. **b.** Joint-plot showing relationship of the groups of floristically similar plots (numbered ellipses, defined by cluster analysis) to environmental gradients depicted by orange vectors in the center of the ordination space showing direction and strength of correlations (r^2 cutoff > 0.2). Plot-symbol colors are according to vegetation types shown in the cluster analysis dendrogram (**Figure 6**). Axes 1 and 2 are labeled with variables correlated with each axis.

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Conclusions

- **Climate-related impacts** influenced the number thermokarst ponds, changes to ice-wedge-polygon morphology, thaw depths, snow depths, dominant vegetation types, and shrub abundance.
- **Road dust** caused large reductions in common moist-tundra diagnostic species, particularly small forbs, mosses, and lichens. The effects of dust were strongly related to distance from the road and were greatest on the downwind side of the road.
- **Flooding** increased permafrost degradation, polygon center-trough elevation contrast, and vegetation productivity.
- While it was not possible to isolate the influence of any of these factors, the combined datasets provide unique insights into the rate and extent of ecological disturbances associated with infrastructure-affected ice-rich-permafrost landscapes under decades of climate warming.
- **Synopsis of changes associated with the four scenarios (Figure 4)**:

Scenario A: Prior to road construction (1949–1968). Analysis of aerial photographs taken in 1949 and 1968 revealed little detectable change in the area of thermokarst ponds, polygon morphology, or vegetation distribution along either the JS or CS transects in the twenty years between 1949 and 1968 (Walker et al. 2015, 2021; Water-body analysis not shown here.)

Scenario B: Climate-related change (1969–present):

- **Changes to thermokarst pond abundance:** The area of thermokarst ponds at the JS site increased 8.3x between 1968 and 2013 at the JS site (Jorgenson et al. 2015) and 6x at CS Transect T1, with a similar rather abrupt increase starting in the 1990s (waterbody analysis not shown here). This change corresponded to a combination of upward trends in air temperature (winter and summer), annual permafrost temperatures, and precipitation (summer rain and winter snow) since the late 1990s. The increases in temperature and precipitation likely led to increase the active layer thickness (ALT = summer thaw depths), resulting in the top surfaces of many ice wedges melting and creating thermokarst ponds (Jorgenson et al. 2006, Walker et al. 2021).
- **Changes to polygon morphology and vegetation distribution:** Melting of the ice wedges caused reduction in the elevation of the polygon troughs relative to the polygon centers and the drainage of water into the troughs, resulting in a shift from low-centered ice-wedge polygons dominated by wet tundra to a transitional high-centered polygons dominated by moist tundra (Walker et al. 2015, mapping analysis not shown here).
- **Change to shrub cover:** Deciduous shrub cover was 5.2 times greater in the CS moist-tundra plots (Walker et al. 2015) compared to comparable plots sampled in the 1970s (Walker 1985) and a 9.6 times greater in the wet-tundra plots (**Figure 6c**).

Scenario C: Climate-related change + road dust (1969–present):

- **Loss of common diagnostic species:** Thirty-two common diagnostic species recorded in moist tundra plots sampled in the 1970s did not occur in plots sampled in 2014, , including many common small forbs, mosses, and lichens that are strongly affected by heavy roadside dust (**Table 1, Figure 7a**).
- **Decreased species richness:** There were 38% fewer species in the CS (2014) moist tundra plots and 46% fewer species in the wet tundra plots compared to similar plots sampled in the 1970s (**Figure 7b**).
- **Changes to growth-form cover:** Pleurocarpous moss cover in CS (2014) moist-tundra plots was 38% of cover reported in moist-tundra plots sampled in the 1970s and 12% of values in wet tundra (**Figure 7c**). Lichens were very sensitive to dust. In the 1970s, lichen cover in moist-tundra habitats (Types U3 and U4) averaged 4.9 ± 0.9%; whereas in 2014, no lichens were observed in any of the Colleen moist-tundra plots within 50 m of the road, and only 3 lichen species occurred with negligible cover at 385 m from the road.

Scenario D: Climate-related change + road dust + flooding (1969–present):

- **Enhanced impacts of climate change to ice-wedge degradation and thermokarst:** Center-rim microrelief, water depths, and snow depths were greatest in troughs on the flooded side of the road.
- **Surface dust layers were thickest** on the T2 (SW and downwind) side of the road with 14 cm in study plots and exceeding 40 cm in some polygon troughs near to the T2 transect.
- **Flooding caused more productive sedge vegetation** with greater leaf area index (LAI) in both the polygon centers and troughs. The enhanced productivity on the flooded side of the road was likely caused by a combination of warmer early-summer soils, deeper thaw, higher rates of organic-matter decomposition, more nutrients from the road, and high inputs of feces and decayed organic matter from the waterbirds that persistently graze the area. Enhanced productivity and erosion of mineral material into the troughs on the flooded side of the road is adding to the litter layer and helping to protect the ice wedges from further thaw (Kanevskiy et al. 2017, 2021).