Long-term landscape impact of petroleum exploration, Melville Island, Canadian High Arctic

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Long-term landscape impact of petroleum exploration, Melville Island, Canadian High Arctic

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Abstract

Industrial land use such as petroleum exploration and infrastructure development has important and lasting impacts on Arctic landscapes. Detailed, site-level investigations have noted impacts that include: vehicle tracks, surface and vegetation alteration, soil compaction, and degradation of ice wedge features. We investigated the long-term impact of an extended period of hydrocarbon exploration on Melville Island in the Canadian High Arctic using available remotely-sensed data supplemented with field observations over a ~370 km² area. Aerial photographs from 1959, 1972, and 1977, and recent satellite imagery (2011 and 2013) were used to determine the effects of industrial activity over periods corresponding to pre-activity, mid-activity, and post-activity. We show that vehicle tracks, site disturbance and vegetative impacts are still evident after 40 years in this area. Permafrost has degraded at sites with concentrated activity (drill sites, airstrips) and changes to vegetation are clearly discernable. The results demonstrate the utility of this approach for assessment of land use impacts on High Arctic landscapes and provide a means to determine locations for more detailed site-specific field studies. These results may contribute to strategies for environmental monitoring in remote areas where access is impractical or resource-intensive.

Keywords: land use impact, hydrocarbon exploration, vehicle tracks, terrain impact, vegetation change, thermokarst, Canadian High Arctic
Introduction

The long-term effects of extended periods of land development or vehicle movement on Arctic environments, particularly in potentially sensitive tundra ecosystems and permafrost landscapes, remain a concern to regulators and communities (ADHR 2004; Jorgenson et al. 2010; Becker and Pollard 2016). With the prospect of future development of natural resources in the Arctic, it is important to understand the impact of industrial activity on land and terrestrial ecosystems in order to mitigate socio-economic and ecosystem impacts. Site-specific studies on landscape and vegetation associated with former airstrips and seismic exploration have documented substantial changes to vegetation, soil properties, and increased active layer depth (Kemper and Macdonald 2009; Jorgenson et al. 2010; Becker and Pollard 2016). Changes to the active layer have resulted in localized permafrost degradation and thermokarst and point to the importance of fine-scale changes in topography, soil properties, and drainage as consequences of surface alteration (Becker and Pollard 2016). These detailed field studies are comparatively resource intensive. In contrast, previous approaches to determining the impact of land activities have shown the utility of available data sources such as aerial photographs (Felix and Raynolds 1989).

Field access is particularly resource-intensive in parts of the western Canadian Arctic Islands, a region known to host approximately 445 billion m³ of natural gas (Kaustinen 1983). The Sabine Peninsula of Melville Island (Nunavut and Northwest Territories) was the subject of extensive exploration between 1969 and 1983 that included seismic surveys and drilling and resulted in the discovery of large natural gas fields (Harrison 1995). The exploration activity was greatest in the 1970s (Harrison 1995) but declined when resource prices collapsed and government incentives changed in the 1980s.

The legacy of industrial activity on the Sabine Peninsula offers an opportunity to investigate the impacts on the landscape and recovery over nearly four decades. The Sabine
Peninsula is underlain by continuous permafrost and presents substantial challenges to trafficability due to unconsolidated fine-grained sediments, frequent saturated soil conditions and varying amounts of ground ice (Stangl et al. 1982). Quantifying the impact of this activity is important for the region as an example of the effects of sustained industrial activity in the High Arctic.

Field-based research has been widely undertaken elsewhere in the Arctic to assess the impacts of land development activities, seismic exploration, and vehicle tracks using field measurements and aerial images (e.g., Abele et al. 1984; Felix and Raynolds 1989; Kemper and Macdonald 2009; Jorgenson et al. 2010). These studies reveal a range of changes to vegetation, soil drainage, and permafrost degradation. Their results highlight the differences between the effects of industrial activities completed at different latitudes and biomes in the Arctic. The long-term effects of industrial activity in the Canadian High Arctic have been investigated in a limited manner (e.g., Becker and Pollard 2016). However, in ice-rich permafrost terrain, commonly associated with the western High Arctic, the effects on the landscape are potentially more pronounced and have a lasting impact especially when activity is completed late in the thaw season with repeated vehicle passes (Rickard and Brown 1974; Slaughter et al. 1990).

This study investigates the long-term effects of vehicular and related industrial activity using remotely-sensed imagery from eastern Sabine Peninsula, Melville Island (Figure 1). The work was initiated following thermokarst field research in the area. It benefits from field observations, but is focused on data sources available remotely. The two primary objectives are to: (1) identify visible vehicle tracks and determine how the tracks have persisted over time through an analysis of historical aerial photographs and contemporary high-resolution satellite imagery; and (2), to assess the impacts of vehicle tracks on the land with terrain metrics and a supervised classification to determine landscape
change. Together, the goals of this work are to document the long-term impacts and recovery of a High Arctic landscape ~40 years post-disturbance and to provide an approach for efficiently identifying areas with comparatively large impacts suitable for focused field investigations.

Study Area

Industrial history

Petroleum exploration by Panarctic Oils Ltd began in the study area in 1969, when an exploration well was drilled. It ended in the mid-1980s, when natural gas prices fell and activity was suspended (Harrison 1995). From this exploration, three primary natural gas fields were delimited: Drake Point, Hecla, and Roche Point fields (Figure 1) (Harrison 1995). Drilling was carried out for over 14 years, with individual wells reaching depths exceeding 4100 m. The drilling involved movement of heavy machinery (such as rigs and drilling platforms), bulldozing and blading for airstrip preparation, permafrost blasting (sump construction) for waste storage, and semi-permanent camp development (Masterson 2013). Transportation for the rigs and supplies was via airlift or by truck and all-terrain vehicle. Eighty-man camps were established with associated airstrips and heavy machinery, including 25 metric tonne crane scales, crawler tractors, forklifts, and Cat trains, all of which were used for travel across the landscape (Masterson 2013). Vehicular traffic was common between the field camps and drilling sites. Operations were year-round, although considerable activity occurred in the winter months when the land surface was frozen and snow covered. However, wells of depths exceeding 4000 m required drilling to continue into the summer months, and as a result, many of the deeper wells on the Sabine Peninsula may have had increased impacts on the landscape (French 1980). Additionally, a notable well blow-out
(uncontrolled gas release and fire) occurred in July 1969 at Drake Point near the eastern coast, and took nearly a year to contain (Clancy 2011).

Environment

The study area is located in the Sverdrup Basin, a succession of marine sedimentary rocks that have undergone limited post-depositional deformation. The Hassel Formation sandstone and Christopher Formation and Kanguk Formation shales outcrop and directly underlie the study site (Harrison 1995). The area is draped with late Quaternary marine and glacial sediments with limited bedrock exposure. Surficial sediments reflect the underlying lithology, leading to distinct topography, soil, and drainage patterns for each underlying bedrock formation (Stangl et al. 1982). Soils below marine limit (~60 m; Lajeunesse and Hanson 2008) tend to be fine-grained, with the majority of the soils in the study area consisting of sands and silty clays. Soils found on northeastern Melville Island have average gravimetric ice contents of 40 - 50%, with the Christopher formation containing between 30 and 70% (Unpublished data). The area is underlain by continuous permafrost with a mean active layer depth of 0.5 to 0.6 m (Stangl et al. 1982). Mean annual air temperature recorded at a temporary station was -16.6 °C for 2011-2012, which is consistent with mean annual temperatures reported from Resolute Airport (-17.0 °C) on Cornwallis Island (Environment Canada 2015). The vegetation is broadly classified as wetlands, tundra, and barrens and is characterized by vegetation that rarely exceeds a few centimetres in height (Edlund and Alt 1989). Vegetation density and community assemblages vary substantially across the landscape, typically due to differences in soil moisture, soil chemistry, and microclimate. In general, the area is sparsely vegetated with herbaceous plants and exhibits the lowest species diversity of the entire island (Edlund and Alt 1989).
Methods

Data Collection

Two Worldview-2 satellite images were acquired as part of a larger project (Rudy et al. 2016): one in 2011 (262 km$^2$) and another in 2013 (107 km$^2$). For temporal comparison, 35 scanned (800 dpi) historical aerial photographs were obtained from the Canadian National Air Photo Library (Ottawa, Canada) (Table 1). Coverage of the satellite image area by the aerial photographs varied by year. The 1959 aerial photographs covered 185 km$^2$ of the satellite images and the 1972 and 1977 aerial photographs covered 48.9 km$^2$ and 194.4 km$^2$, respectively. There were 32 km$^2$ of overlap between the 1959, 1972 and 1977 aerial photographs and the satellite imagery. Aerial photographs were georeferenced to the satellite images using ArcGIS (ESRI, version 10.2.2). As ground control points (GCPs) were unavailable, the images were manually georeferenced using fixed terrain reference points. Between 5 and 8 GCPs were selected throughout the image using clearly defined physical features that were unlikely to change over time (i.e. bedrock outcrops and gullies) to match each aerial image to the corresponding satellite image. More reference points were assigned for photographs in areas with greater elevational change to minimize spatial distortion. Georeferencing errors were within ~1 pixel for each image. The average error for the 1:60,000 (1959), 1:12,000 (1972) and 1:15,000 (1977) aerial photographs were 2 m, 0.5 m and 0.5 m, respectively.
Digital elevation models (DEM) were derived for the study area using the high-resolution stereographic Worldview-2 images collected in 2011 and 2013. The 2011 DEM was produced using a proprietary stereo image matching process (processed by PhotoSat, Vancouver, Canada) and the 2013 DEM was created using Geomatica software (PCI Geomatics, version 2013). Both DEMs have horizontal and vertical resolutions of 1 m, which were then aggregated to 2 m (horizontal resolution) to increase processing efficiency (Rudy et al. 2016).

**Study Design**

This study was designed using a combined before/after (BA) time series and a control/impact (CI) approach. The BA approach uses pre-activity data (1959 photographs), mid-activity data (1972/1977 photographs), and post-activity data (2011/2013 satellite images). The CI approach involves comparing an impacted area (i.e., the vehicle tracks) to non-affected areas, or control areas (i.e., the non-disturbed track buffers). The BACI method is typically used as a means for testing whether a change has occurred and how much impact it has had on the study area (Smith 2006). Tracks were mapped using recent satellite imagery and compared to historical aerial photographs. To ensure consistency, track mapping was completed by one person and verified separately by the co-authors. Vegetation cover class changes associated with the tracks were examined using spectral analyses and compared to the same area prior to activity.

Field studies at this location were undertaken prior to this research (2010-11) and provide anecdotal observations regarding the nature of impacts that remain on the landscape (Figure 2). These observations indicate clear visual impacts on the landscape, but do not provide detailed site-specific investigation of these effects.
Mapping of tracks, disturbances and drill sites

A 1.9 km$^2$ grid was imposed over the study area to systematically analyse the images for vehicle tracks. Based on preliminary mapping, two types of track were mapped: single tracks (ST) and multiple tracks (MT) (Figure 3). ST were mapped as a discrete line features (Figure 3A and 3B). MT have three or more tracks visible within a 10-metre zone (Figure 3C). To delineate the multi-track areas, a 10-metre buffer was centred on a central line of the set of tracks (Figure 3D). This approach was carried out to avoid ambiguity when multiple tracks were present. Both types of tracks were mapped for each time period, resulting in a total of three track maps: 1972, 1977, and 2011/2013 (hereafter referred to as “recent”). There were no tracks on the pre-activity 1959 aerial photographs.

Additionally, two types of permafrost disturbances were mapped with the recent imagery: retrogressive thaw slumps, in which exposed ice creates a recurrent slope failure (Burn and Lewkowicz 1990), and active layer detachments (ALD) that result when the thawed active layer slides downslope over the underlying permafrost (Rudy et al. 2016). These permafrost disturbances were mapped to measure the possible association between slope failures and vehicle activity across the landscape. Petroleum exploration well site collar locations were mapped using data from Harrison (1995).

The total length (km) of visible tracks was computed for each of the mapping years and the changes were calculated to measure the longevity of tracks over time. Photograph coverage varied by year and did not cover the entire study area defined by the satellite images.
Calculations and reported track values were only enumerated for the respective photograph coverage extents. Additionally, track density maps were generated in ArcGIS using the line density function for each of the years (km/km²) to compare temporal changes.

*Effects of tracks on the landscape*

The long-term impacts of industrial activity were examined using tracks mapped on the recent imagery and two terrain variables including the Normalized Difference Vegetation Index (NDVI) and a topographic wetness index (TWI). Untracked areas adjacent to mapped ST and MT were extracted using a 10 m buffer to examine the impact of tracks on the terrain (Figure 3). Two additional variables, a permafrost disturbance susceptibility map and an elevation map, were included to determine if there was a pattern in landscape disturbance risk related to the location of both types of tracks.

Normalized Difference Vegetation Index (NDVI) was used to measure changes in vegetation cover and biomass production. NDVI accounts for different absorption and reflectance characteristics of vegetation in the red and near infrared regions (Tucker 1979). The output values ranged from -1 to 1, with 1 indicating high estimated levels of vegetation and -1 representing non-vegetated surfaces (i.e., rock and soil). The TWI serves as a proxy for soil moisture and was calculated using DEM-derived hydrological flow paths and upslope contributing areas in Whitebox Geospatial Analysis Tools (Lindsey 2012). An FD8 flow algorithm was applied to represent the flow of water into multiple neighbouring cells based on slope concavity or convexity and determines an index of surface saturation at each cell (Beven and Kirkby 1979).

A statistical permafrost disturbance susceptibility model, developed to determine landscape susceptibility to permafrost slope failures was used to identify if there was an association between the location of tracks and modelled disturbance susceptibility. The model
was developed for the north (2011) satellite image by Rudy et al. (2016) and the same methodology was applied to the south satellite image (2013) area to estimate the probability of slope disturbance. The statistical model relates the occurrence of existing slope disturbance to terrain metrics and applies this statistical relationship to the landscape, identifying areas with varying degrees of susceptibility to future disturbance. Additionally, elevation values were extracted from the DEM to serve as a proxy for Holocene marine limit. Soils below marine limit are usually characterized by higher silt, clay, and ground ice contents compared to areas above marine limit. For all calculated terrain and model metrics, mean values were extracted for the mapped 2011/2013 ST and MT areas and the adjacent untracked areas.

Landcover Change

A supervised classification was completed to examine inferred vegetation change associated with industrial activity. A supervised classification was necessary to account for the different image types (aerial photographs and satellite imagery) and their inherently different spectral characteristics. This classification approach was used to provide a means of identifying relative change between image types, which we broadly characterize as a reduction in vegetation cover. We were unable to distinguish specific aspects of vegetation from this approach, but could identify relative brightness differences, of which the most probable was the change from bare soil (light tone) to vegetated (darker tone). Darker tones are often associated with wetter soils, which are commonly linked with vegetation in this arid High Arctic ecosystem (Allux 2012). These classes were distinguished using knowledge of the vegetation communities (Allux 2012), spectral signature comparisons, soil moisture, and NDVI from the satellite image.

Spectral signature files were created for each image (aerial photographs and satellite images) in ArcGIS by selecting areas of change to train the classification. Six classes were
generated: snow, bare soil, sparse vegetation, medium vegetation, dense vegetation, and water. In the satellite images the three vegetation classes were differentiated by differing tonal signatures, with lighter tones indicating less vegetation. To generate a classification for the greyscale aerial photograph spectral signature files, we separated the image according to digital number. Areas with sparse to no vegetation density were characterized by high digital numbers and appeared bright (i.e. light grey and white tones); areas with higher vegetation density had lower digital numbers and lower image brightness (i.e. dark tones). For the satellite images, the same process was used to generate spectral signatures using NDVI as a reference. Classes were then merged into two classes representing very sparse to sparse vegetation and no vegetation (i.e. snow, bare soil and water). The classified images were subtracted to generate a three-class output indicating whether there had been an increase in vegetation, a decrease in vegetation, or whether the vegetation had remained relatively unchanged.

Results and Discussion

Track longevity and change

Tracks are still clearly evident on the landscape both remotely and from the ground forty years after activity ceased (Figure 2 and Figure 3). The tracks mapped within the area of image overlap (32 km$^2$) decreased from 105 km in 1972 to 102 km in 1977 and 93 km in the recent imagery (Table 2). This decrease is primarily related to the recovery of ST; the length of mapped MT minimally increased over the time interval (Table 2). The recovery of single tracks corresponded to the degree of initial impact. These locations were less heavily trafficked and the overall impact on the landscape was lessened leading to increased track recovery. In both the time intervals, 1972-1977 and 1977-recent, there was an increase in
mapped MT of ~ 8% (Table 2). This increase in MT reflects both drilling activity and a shift of ST to MT. A number of these MT locations were corridors between drill sites and field camps indicating their frequent use that led to greater and longer lasting impact. Additionally, land use activity associated with well sites increased after the aerial photographs were taken, accounting for the increase in MT. Overall, the persistent visibility of the tracks from the 1970s indicates that the recovery has been slow, but total track length has indeed declined.

<Table 2>

The overall track density is similar for the three different time periods with the exception of the multi-well site (Figure 4). At this location, three wells with depths ranging between ~2000 and 3500 m were drilled over numerous seasons (1969 – 1973) and the area would have been heavily trafficked during this period. Although the 1972 aerial photographs did not cover the extent of the multi-well site, the density mapped in 1977 is likely representative of tracks that would have been present in 1972.

<Figure 4>

Impacts of tracks on the landscape

The removal or compaction of vegetation in tracks made by off-road vehicles can lead to changes in a site’s physical characteristics, particularly in the first decade after disturbance (Abele et al. 1984; Lawson 1986; Keven et al. 1995). The impact on and recovery of the terrain will vary depending on the severity of the initial disturbance, though the effect over a longer time scale may be negligible. TWI and NDVI values extracted from tracked and adjacent untracked areas showed minimal measurable differences over a 40-year period. Both
ST and MT zones had slightly higher mean TWI values compared to their adjacent untracked areas (6.6±1.6 and 6.4±1.5 compared to 6.5±1.7 and 6.3±1.6 respectively) although not statistically significant. Tracking from off-road vehicles may promote hydrological erosion and the development of rills or gullies concentrating surface flow (Stangl et al. 1982; Woo 1986). The mean NDVI in tracked and untracked areas for both ST and MT was 0.2±0.1 indicating the recovery of vegetation in the disturbed areas. While there are visual impacts on the landscape, the measured mean physical differences between tracked and untracked areas are small (<0.1 for TWI, <0.01 for NDVI) suggesting that while the tracks have not completely recovered, they have stabilized 40 years post-disturbance. The persistence of track visibility could be due to a difference in vegetation structure and topsoil compaction, though fieldwork would be required to confirm this.

Thermokarst and Permafrost Degradation

Comparison of track locations and modelled disturbance susceptibility (Rudy et al. 2016) suggests that selective route choice may have resulted in traffic using areas that were less vulnerable to slope failure. Both ST and MT were located in very low susceptibility zones, indicating that the terrain was relatively stable. The more frequent location of both types of tracks compared to surrounding untracked areas may also reflect route selection by individual drivers. However, it is clear that many of the conditions conducive to slope failure were generally avoided by vehicles (i.e. moderate to steep slopes and wet conditions).

The limited association between track locations and permafrost slope disturbances indicates that it is unlikely vehicle activity contributed to these features. Less than 1.3 km (0.5%) of both MT and ST (out of a total of 257 km) mapped on the recent image crosses over either disturbance type (n = 2). Slope failures such as active layer detachments and retrogressive thaw slumps have been noted widely on the Sabine Peninsula (Rudy et al.)
2016), elsewhere on Melville Island (Lamoureux and Lafrenière 2009) and in the North American Arctic (Bowden et al. 2008; Lantz and Kokelj 2008; Lacelle et al. 2015). These disturbances to the land surface have been associated with recent climate change, particularly deeper active layer development and increased rainfall (Lamoureux and Lafrenière 2009). The widespread occurrence of ALDs on the Sabine Peninsula also appears to be caused by regional climate change. This study does not suggest that these disturbances have resulted from historical land use.

There is, however, some thermokarst degradation of ice-wedge polygons and visible ponding in very high-activity areas such as the multi-well site and the airstrip (Figure 5). Thermokarst features are localized and account for 0.72 km$^2$ or 35% of the overall area at these sites (2.04 km$^2$). In heavily trafficked areas the probability of ground ice thaw and subsidence is greater (French 1975). This is consistent with expected effects in areas subject to repeated activity or soil movement work with heavy equipment (Rickard and Brown 1974; Keven et al. 1995). Evidence of thermokarst and ponding indicates that sustained or high levels of activity may change the surface in a lasting and visible way.

Figure 5

Vegetative change detection analysis

The supervised classification was effective at identifying inferred vegetation change for the highly trafficked multi-well site and airstrip (Figure 6 A and B). Both of these areas would have had sustained activity and complete or partial removal of vegetation. Although tracks remain visible from vehicle activity in relatively undisturbed terrain, there was limited impact on ground cover spectral properties. Little vegetation change associated with individual tracks was observed during ground visits to many of the tracks (Figure 3). These results suggest that the tundra communities in the study area are resilient to one-time or
infrequent vehicle traffic. While this analysis was useful for classifying these broad zones of change, it was unable to classify small areas of change accurately, including ST, due to exposure imbalances in the photographs and landscape change related to stream channels, residual snow cover, and small georeferencing errors that complicated the interpretations of landscape change.

*<Figure 6>*

The change detection analysis reveals substantial localized impacts associated with sites where an airstrip was located and where multiple drill holes were completed. These areas, despite the limitations of image comparisons (see next section) show clear, widespread surface changes that are likely related to vegetation disturbance as well as subsurface alteration (Felix et al. 1992; Keven et al. 1995; Lee & Boutin 2006; Kemper & Macdonald 2009). Development of ice wedge troughs and surface ponding in the concentrated drilling site and airstrip (Figure 5) indicate that the surface disturbance may have also altered active layer thaw conditions and enhanced permafrost degradation, as is likely when surface conditions are disturbed (Mackay 1970). These changes could have been due to soil compaction (Lawson 1986), surface drainage alteration, or changes in snow cover retention that served to alter the physio-thermal conditions in the active layer (Keven et al. 1995). In heavily impacted areas greater surface disturbance was associated with water impoundment and ice-wedge degradation than on slope thermal erosion processes. It is not clear if these impacts caused permafrost degradation directly, or if they contributed to enhanced sensitivity of these locations to regional climate warming-induced degradation. The results are consistent with cases elsewhere where thermokarst has been associated with surface disturbance such as following aggregate extraction or other surface alteration (e.g., French
1975; Becker and Pollard 2016). More broadly, these intense land surface alterations are recognized as increasing the risk of permafrost degradation and infrastructure instability (Mackay 1970; Raynolds et al. 2014; Lamoureux et al. 2015; Becker and Pollard 2016). Results from this study demonstrate localized areas where permafrost degradation can be associated with past land use and indicate the risk of these intensive activities for landscape stability in Arctic regions.

Collectively, results from this study indicate that the long-term impact from vehicle tracks largely remains after 40 years in this High Arctic environment. While some tracks are no longer visible on the landscape, many remain including areas where multiple tracks occur. Tracks are generally constrained to broad corridors between drilling areas, airstrips and camps while other areas remain essentially unaffected by historical activity.

Limits to detecting change in Arctic landscapes

Several limitations are inherent with this type of study and have implications for future research. First, each aerial photograph set had different scales (Table 1) and it is possible that tracks visible in one set will not be visible in another. However, these minimal differences in scale are unlikely to influence the outcome of the temporal mapping. Second, this approach could not remotely measure factors such as changes to active layer depth, which is proven to be altered by tracks over the long-term (Keven et al. 1995). Alternatively, the tracking may predispose these areas to rainfall runoff or permafrost degradation processes that may become more frequent in the future (Jorgenson et al. 2010). Third, an inherent limitation with aerial photographs is the lack of a consistent exposure over individual photographs and between photographs. In this study, areas with sparse vegetation coverage are overexposed while areas around the photo edges are underexposed. In addition, the angle
of surface reflectance influences exposure and can limit spectral classification. Thus the analysis is better suited to detection of large changes.

To accurately compare the current and future impact of development activities in these areas, efforts should be made to ensure consistent remote sensing data are acquired. When aerial photographs are used during reconnaissance and the initial development stages, future photograph acquisitions should be considered to provide more effective direct comparisons. The same principle applies for satellite imagery acquisitions, however this represents a new challenge when space-borne imaging systems continue to evolve and sensor and spatial resolution tend to increase. Notwithstanding these challenges, determining impacts can be facilitated by proactively planning suitable data collection to minimize uncertainties in results.

Conclusions

This study has shown that 14 years of intensive oil and gas exploration activity has left a clear legacy of residual vehicle tracks in broadly defined travel corridors, along with localized areas of vegetation change and thermokarst activity in areas of sustained activity including an airstrip and locations where multiple deep wells were drilled. Vehicle tracks remain visible on satellite imagery 40 years after activity ceased but are associated with minimal thermokarst or permafrost degradation. Thermokarst located within intensively occupied areas was evident primarily as ice wedge degradation and reduced vegetation cover. The persistence of these visible indicators of change decades after activity ended suggests that even poorly vegetated areas in the High Arctic are susceptible to long term disturbance.

The results indicate that a remote sensing-based approach to change detection is effective for determining the location and relative intensity of impacts from past land use in the High Arctic. Vegetation change is difficult to quantify from historical aerial photographs
and contemporary multi-spectral remote sensing imagery, but relative vegetation changes can be discerned using supervised classification techniques. These methods are suitable where field studies are not possible or as a preliminary strategy to identify the most important areas for field-based investigations. Hence, this approach indicates an important means of preliminary screening suitable for feasibility or planning stage efforts to minimize the impact of future development on the land and vegetation. Locations of intensive activity show both substantial surface impacts, and appear prone to subsequent permafrost change and thermokarst development, while lower intensity activities such as the passage of vehicles leave lasting impacts. Policy efforts to minimize development impacts should reflect the intensity and duration of proposed land uses and appropriate mitigation requirements should be considered given the likely different long-term outcomes.

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Table and Figure Captions

**Table 1** Aerial photograph and satellite scales or resolution and dates of acquisition.

**Table 2** Total mapped single-track (ST) and multi-track (MT) lengths for 1972, 1977 aerial photographs and for the recent satellite imagery within the area of overlap (32 km$^2$). No mapped tracks were mapped in 1959. Negative values indicate a decrease in total track amounts and positive values indicate an increase in total track amounts.

**Figure 1** Extent of the study area on the eastern Sabine Peninsula. The location of the natural gas fields on the Sabine Peninsula and their extension into the ocean as well as the satellite image extents are outlined in the top right inset. Yellow stars denote wells; completed wells are identified by their date of completion and depth in metres. Heavily travelled areas are outlined in red, the rectangle represents a previously active airstrip and the circle is an area of heavy drilling activity. Base image is a mosaic of the 2011 and 2013 Worldview-2 (©DigitalGlobe) panchromatic images (0.5 m resolution).

**Figure 2** Examples of single tracks (A), multi-tracks (B) and tracks crossing an active layer detachment (black dashed line) (C). A producing well site is shown in (D) with the track leading to the well site highlighted in (E). The impact of heavy machinery being dragged across the tundra in the late season is evident through the displacement of the original active layer.

**Figure 3** Examples of unmapped and mapped single tracks, (A) and (B); unmapped and mapped multi-tracks, (C) and (D). Background image is Worldview-2 panchromatic imagery (0.5 m resolution).

**Figure 4** Progression of tracks from 1972 to 2011/2013 represented as track density. Tracks may be missing from aerial photographs due to incomplete coverage. The coverage of each aerial photograph acquisition is outlined by the grey rectangles.

**Figure 5** Evidence of change at the airstrip and the multi-well site in the 1959 aerial photograph (A) and (D), 1977 aerial photograph (B) and (E) and 2011 satellite imagery (C) and (F). The photograph edge is evident in (E) by the linear change in tone.

**Figure 6** Complete or partial removal of vegetation at the heavily trafficked multi-well site (A) and airstrip (B) between 1959 and the recent imagery is identified by red. Well sites in (A) are denoted by the yellow stars.
Table 2 Aerial photograph and satellite scales or resolution and dates of acquisition.

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<td>1:15 000</td>
<td>0.48 m</td>
</tr>
<tr>
<td>$A_{24720}$: 006, 056, 059, 065, 067, 103, 105, 107, 112, 114, 116, 118, 145</td>
<td>1977</td>
<td>Greyscale</td>
<td>1:15 000</td>
<td>0.48 m</td>
</tr>
<tr>
<td>Worldview-2 (north)</td>
<td>2011</td>
<td>Panchromatic</td>
<td>0.5 m</td>
<td>--</td>
</tr>
<tr>
<td>Worldview-2 (south)</td>
<td>2013</td>
<td>Panchromatic</td>
<td>0.5 m</td>
<td>--</td>
</tr>
</tbody>
</table>
Table 2 Total mapped single-track (ST) and multi-track (MT) lengths for 1972, 1977 aerial photographs and for the recent satellite imagery within the area of overlap (32 km²). No mapped tracks were mapped in 1959. Negative values indicate a decrease in total track amounts and positive values indicate an increase in total track amounts.

<table>
<thead>
<tr>
<th>Track Type</th>
<th>1959 (km)</th>
<th>1972 (km)</th>
<th>1977 (km)</th>
<th>Recent (km)</th>
<th>1972 to 1977 (% change)</th>
<th>1977 to Recent (% change)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST</td>
<td>0</td>
<td>56</td>
<td>49</td>
<td>35</td>
<td>-12.5</td>
<td>-28.5</td>
</tr>
<tr>
<td>MT</td>
<td>0</td>
<td>49</td>
<td>53</td>
<td>58</td>
<td>7.5</td>
<td>8.6</td>
</tr>
</tbody>
</table>