A REVIEW ON VEGETATION DAMAGES CAUSED BY ANTHROPOGENIC DISTURBANCES IN THE TERRESTRIAL ARCTIC

– with recommendations for best practices to minimize vegetation damage from driving with heavy equipment

Scientific Report from DCE – Danish Centre for Environment and Energy No. 485 2022

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Abstract: This report describes the potential environmental impacts from surveying with heavy vehicles in Arctic areas (Canada, Alaska, Greenland), the environmental regulation in these areas and lessons learned from seismic surveying in Jameson Land, East Greenland in the 1980ies.

Keywords: Onshore seismic surveys, environmental impacts, vegetation damage, permafrost, thermokarst, authority regulation, Alaska, Canada, Greenland

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Contents

Preface

This review project was initiated by DCE – Danish Centre for Environment and Energy to provide up to date information on how to minimize the impact of onshore seismic surveys on vegetation, and it was funded by the Ministry of Environment of Denmark. The review provides general information on vegetation sensitivity to driving by heavy vehicles, which is relevant for mining operations in the Arctic. At the time this project was initiated, seismic surveys was anticipated in Jameson Land, where seismic surveys had also taken place in the 1980ies. It was therefore pertinent to look at the experience from Jameson Land as well as in other Arctic areas to provide guidance on sensitivities and potential regulation which could minimize effects on vegetation. The report is a background study supplementing the advisory report to the Greenland government (Environmental Agency for Mineral Resource Activities, EAMRA): *Onshore Seismic Surveys in Greenland, background information for preparation of guidelines to environmental impact assessment* (Kyhn et al. 2020).

Summary

This report reviews the knowledge on vegetation and terrain damage from anthropogenic activities in the Arctic based on information from Alaska, Canada and the seismic surveys carried out in Jameson Land, East Greenland in the 1980ies based on peer-reviewed literature as well as on “grey” literature such as scientific advisory reports.

The present report gives an overview of the most significant elements of the Arctic in the context of vegetation and terrain damage: Permafrost, the active layer above the permafrost, the vegetation and the terrain, and it is underlined that an intact vegetation cover is the key to maintaining the thermal balance between the active layer and the permafrost, which is the most crucial aspect for restoration.

This is followed by an overview of vegetation damages and the effects on the deeper layers below – the active layer and especially the permafrost and on hydrology. Different activities (incl. oil spills) and their potential for vegetation damages are described, with focus on driving and transport of heavy equipment.

Methods for assessing vegetation damages and ways to re-establish vegetation are briefly described.

The report reviews the authority regulation related to protection of vegetation in Arctic Canada and Alaska, followed by a description of the previous regulation in Greenland when seismic surveys took place in Jameson Land, East Greenland in 1980ies. The regulation then was based on background studies in the affected area and on the regulation experiences from Canada and Alaska.

It is concluded, that no serious long-term effects of the winter seismic surveys in Jameson Land have been found in terms of vegetation cover or erosion. In that sense, the regulation was a success. Some of the main concerns about the wet terrain and vegetation types are not confirmed, while the dry heaths with frost sensitive species like *Cassiope tetragona* turned out to be more sensitive with damages still visible after 30 years, a fact not anticipated or considered in the regulation.

The lessons learned then are summarised and together with the Canadian and Alaskan regulation give rise to recommendation of some new best practices to avoid vegetation damages from use of heavy vehicles in Greenland.

The key factors to avoid or minimize vegetation damages in winter are the depth of the snow layer and freeze up of the ground and soil beneath the snow, and it is recommended that activities with heavy vehicles cannot be initiated until:

- The ground is frozen, i.e. the temperature shall be -5 °C at 30 cm soil depth,
- Snow depth is at least 25 cm in all terrains.

However, local conditions may change these figures.

Regarding summer seismic surveys on land, DCE and Greenland Institute of Natural Resources (GINR) generally recommend that they are avoided and carried out in winter instead, when the terrain is frozen and snow-covered.

Finally, the report identify some relevant research needs to be addressed in relation to regulation of activities with heavy vehicles, such as seismic surveys:

- In areas where activities are planned: Vegetation mapping including ground-truthing of vegetation types, occurrence of red-listed plant species, mapping of snow depths and annual freezing of the active layer,

- The sensitivity of various high Arctic vegetation types to driving activities both summer and winter. In the latter case especially under different snow regimes including compaction of snow.

Sammenfatning

Denne rapport giver en oversigt over de skader menneskelige aktiviteter kan påføre vegetation og terræn i Arktis. Den er baseret på viden primært fra Alaska og arktisk Canada, samt fra seismiske undersøgelser udført i Jameson Land, Østgrønland, i 1980erne.

De vigtigste elementer i denne sammenhæng i Arktis gennemgås: Permafrost, det aktive lag over denne, vegetationen og terrænet. Det understreges at vegetationen er afgørende for bevarelsen af permafrostlaget.

Der gives en oversigt over forskellige skader på vegetationen og de skader på de dybere lag og hydrologien, som de kan medføre. Forskellige aktiviteter, og den risiko de medfører for skader på vegetationen, beskrives med fokus på kørsel og transport af tungt udstyr.

Metoder til vurdering af vegetationsskader og til retablering af ødelagt vegetation beskrives kort.

Myndighedsreguleringen i forbindelse med beskyttelse af arktisk vegetation i Alaska og Canada beskrives og det følges af en omtale af reguleringen af seismiske undersøgelser i Jameson Land i Østgrønland i 1980erne. Denne var baseret på grundige baggrundsundersøgelser og på den daværende regulering i Canada og Alaska.

Senere undersøgelser konkluderer, at der ikke opstod væsentlige langtidsvirkninger af de seismiske undersøgelser i 1980erne, og at reguleringen dermed virkede. Desuden viste det sig, at bekymringerne for nogle af de primært fugtige plantesamfund var ubegrundede, ligesom det viste sig, at særligt kantlyng-hederne var sårbare over for, at snedækket over dem blev trykket sammen og dermed mistede isolationsevnen. Dette tog reguleringen ikke højde for, og disse skader ses endnu 30 år senere.

De indhentede erfaringer sammenholdt med den nuværende regulering i Alaska og Canada giver anledning til forslag til nye reguleringstiltag ved kørsel om vinteren med tunge køretøjer på land i Grønland. Det gælder primært om at undgå eller minimere skader på vegetationen, og her er dybden af snelaget og den underliggende jords grad af nedfrysning afgørende. Det foreslås, at kørsel undgås indtil:

- jordtemperaturen er under -5 °C i 30 cm dybde, og
- snelaget er mindst 25 cm i alle terræner.

Men lokale forhold kan spille ind og give anledning til andre mål.

Om sommeren anbefales det helt at undgå kørsel, sådan at seismiske undersøgelser begrænses til vinterperioden, når jorden er frosset og snedækket.

Endelig identificeres nogle videnshuller, som bør adresseres i forbindelse med seismiske undersøgelser eller andre aktiviteter med tunge køretøjer:

- kortlægning af sårbar vegetation, snedybder og indfrysning af det aktive lag,
- forskellige højarktiske plantesamfunds sårbarhed over for kørsel sommer og vinter, herunder sammenpresning af sne ved etablering af sneveje.

Eqikkaaneq

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1 Introduction

This report reviews the existing literature on vegetation and terrain damages as a result of human-made disturbances from activities such as seismic surveys and mineral extraction, including off road driving on the tundra – and the potential for recovery. The greatest challenge of this review is the age of the included material. Most cited work are peer-reviewed articles and reports of studies performed just before the turn of the century. The reason for this is that oil and gas extraction from terrestrial sites in the Arctic began in 1950ies in Alaska and Canada, where a wealth of studies were performed to inform the authorities on how to extract for example oil with the least impact on the environment. The first activities in the early 1950ies caused tremendous damage to the tundra in terms of melting permafrost, thermokarst and changes to the vegetation. Damages that are still visible today. These early studies quickly lead to guidelines on how best to manage heavy vehicles in areas with permafrost, and since the turn of the century rather few peer-reviewed articles has been published on this topic. This is most likely a consequence of the thorough and comprehensive studies performed from 1959-1990ies. Secondarily, it is an effect of the focus on climate change that began from the 1990ies. Many of the relatively old studies are included here as they represent state of the art within the field of Arctic vegetation damages. Thus, this review covers material from the period 1950 to 2020, with the majority of papers produced in the 1970-80ies.

Many of the early studies focused on damage to the permafrost layer, and the results are relevant to large areas in Greenland. But notice that permafrost is lacking or is sporadic in the southern part of Greenland (Figure 1).

The review is intended to be read chapter wise. This means that there is some repetition among chapters. The review begins by setting the scene in terms of the abiotic Arctic conditions for plant life. Hereafter the relationship between vegetation damages and derived effects such as changes to hydrology, permafrost and thermokarst are explained. The review also covers effects of oil spills on vegetation, which can be from exploration and extraction of oil on land, from pipelines or fuel storages or from transportation by trucks.

Causes of vegetation damages are reviewed midway. Hereafter, the regulation of heavy equipment use in the North American Arctic is reviewed and compared with the regulation exerted in Greenland in the 1980ies. The review concludes with a chapter on recommendations for best mitigation practices for avoiding vegetation and terrain damages.

2 The Artic environment in relation to vegetation damages

The Arctic environment (defined here as areas with mean July temperature below 10 °C) is in many aspects very different from temperate and tropic regions. In relation to vegetation damages and regrowth; permafrost, hydrology, natural succession and physiology of Arctic plants plays crucial roles, and these factors as well as many more important aspects will be introduced in the following chapters.

2.1 Permafrost

Most of the Arctic land area is characterized by permafrost (Figure 1). Permafrost is defined as ground (rock or soil) with temperatures remaining at or below 0 °C for two or more years (Goudie, 2004). Vegetation plays an important role for permafrost: Ground temperature is closely linked to air temperature, however the plant cover acts as a buffer and insulates the ground during fluctuating air temperatures (Walker et al., 2003). The thicker the vegetative mat, the less correspondence between air and ground temperature, and opposite. This means that if the plant cover is removed, the temperature of the ground will increase in summer, which may disrupt the permafrost, change hydrology and accelerate the disruption of the plant cover for whatever reason it occurred. This is the focus of chapter 2.5.

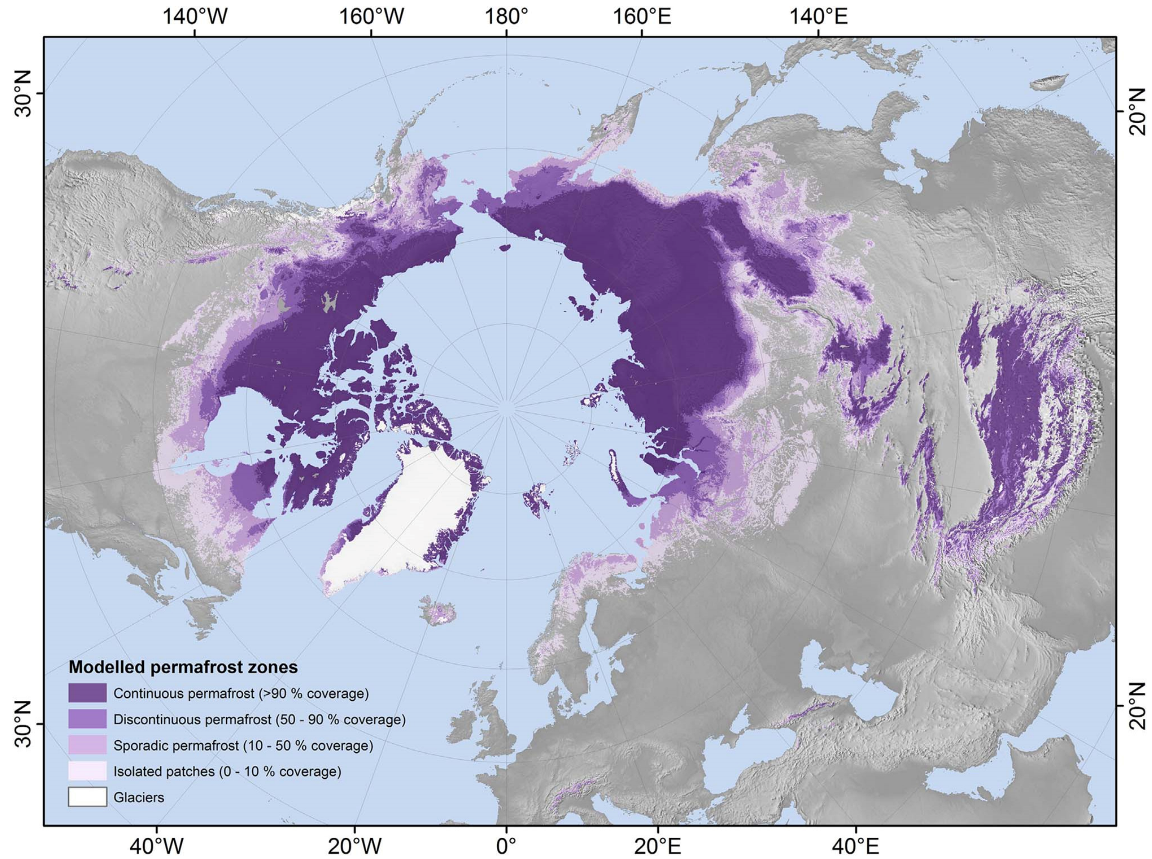


Figure 1. Modelled permafrost zonation in the northern hemisphere. Note the extent of continuous, discontinuous and sporadic permafrost. The model estimated permafrost distribution at a hemispheric scale, by employing an equilibrium state model for the temperature at the top of the permafrost (TTOP model) for the period 2000–2016, driven by remotely-sensed land surface temperatures, down-scaled ERA-Interim climate reanalysis data, tundra wetness classes and landcover map from the ESA Landcover Climate Change Initiative (CCI) project. From (Obu et al., 2019).

2.2 Active Layer

The upper part of the permafrost ground that thaws every summer is called the active layer (Figure 2). The active layer is a pre-requisite for plant growth as the thawed ground allows for nutrient flow from metabolizing microorganisms active at temperatures above freezing, melted water and enzymatic activity in the plants themselves required for growth. For example artificially increasing ground temperature, keeping all other parameters constant, increased the above ground total plant mass; the higher the temperature, the larger the plant mass (within the experimental ranges tested) (Brooker and van der Wal, 2003).

The active layer varies in depth from about 40 cm in Arctic deserts to 100 cm in wet areas depending on summer temperatures and soil type. The moister the soil, the deeper the active layer (in the same climate). Moist south facing slopes have the deepest active layer. At a depth of 15 m below the ground surface the temperature is stable year round and this depth is termed the *zero annual* amplitude (or Base of permafrost in Figure 2). Between the surface and the zero annual amplitude, the temperature can vary between 0 to -16 ^{o}C, but is generally related to the annual mean air temperature. Below the zero annual amplitude at 15 m depth, temperature increases with app. 1 ^{o}C per 30-40 m (Møller and Strandberg, 1991). The water content of the active layer varies with depth. There is a moisture gradient from dry at the surface to wet at the permafrost interface. This is because the water evaporates or is taken up by plants at the surface, whereas water sinks downwards towards lower temperatures. Because water conducts heat more readily the moisture gradient established during thaw is enhanced by subsequent gradual increases in the thermal regime as the season progresses (Babb and Bliss, 1974). The active layer is therefore expected to increase in response to warming temperatures (Hollesen et al., 2011).

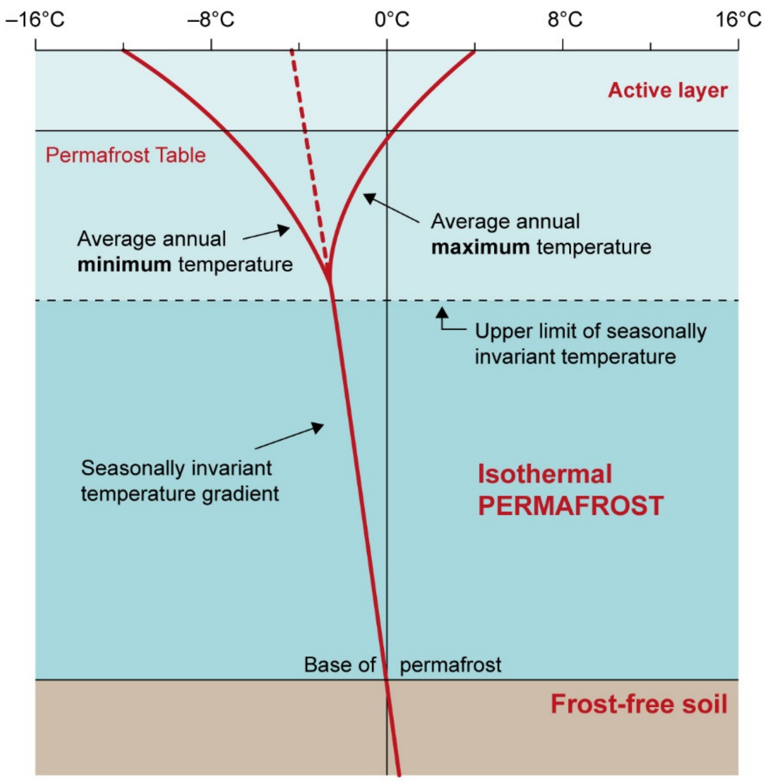


Figure 2. Schematic drawing of active layer, permafrost and frost-free soil. Picture is from https://en.wikipedia.org/wiki/File:Vertical_Temperature_Profile_in_Permafrost_.

The active layer has been measured in Zackenberg, Northeast Greenland (74° N) at specific positions (ZERO CALM 1 & 2) every summer since 1995 as part of the Greenland Ecosystem Monitoring (GEM) program. Figure 3 displays raw data for active layer at Zackenberg from all measuring years and a linear trend in increasing thaw depth is apparent from 1995 to 2017 with an increase in active layer of 0.99 cm / year. From 1995 to 2010 the active layer increased 0.67 m relative to the long-term mean (Shiklomanov et al., 2012). At another GEM monitoring station at Nuuk (64° N, Low Arctic), there is no permafrost.

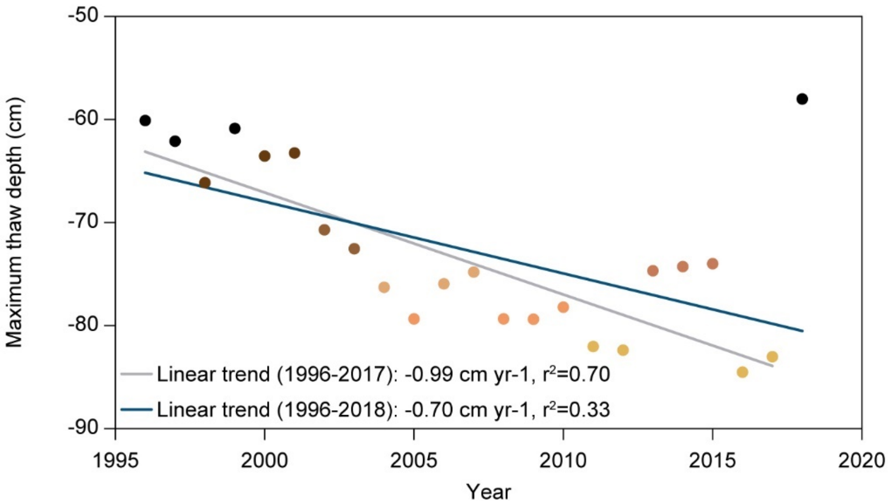


Figure 3. Maximum yearly extend of active layer, or thaw depth, at Zackenberg, Northeast Greenland. The active layer is measured below different vegetation types (indicated by the colours). Figure from GEM Report Cards 2018 (http://g-e-m.dk/fileadmin/g-e-m/GEM/Report_Cards 2018_web.pdf).

2.3 Permafrost distribution

In the northern hemisphere there are vast areas with continuous permafrost as well as areas with discontinuous and sporadic permafrost (Figure 1). The distinction between continuous and discontinuous permafrost depends on the extent of the permafrost measured as percent of the area covered. There are several different definitions on how to define these zones. Here, we follow (Harris, 1986):

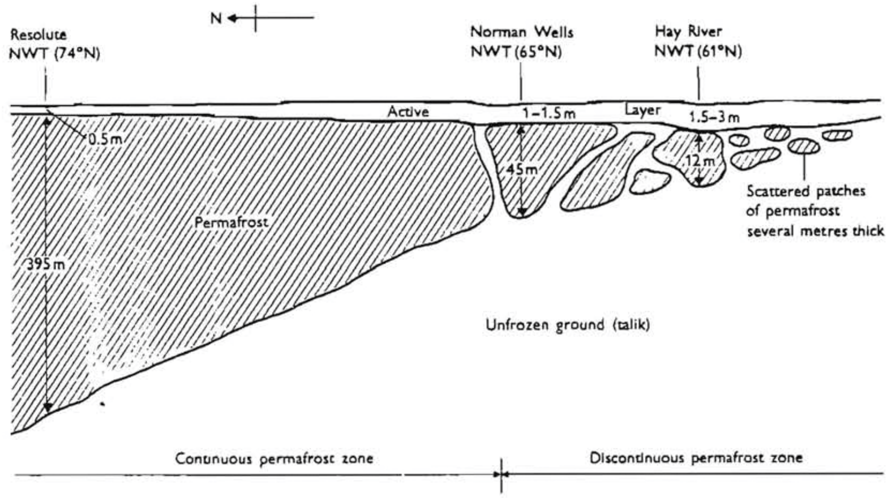
- Continuous permafrost has an area coverage of > 80%,
- Discontinuous permafrost has an area coverage of 30-80%,
- Sporadic permafrost has an area coverage of < 30%.

Generally speaking, the higher the latitude, or altitude, the higher the degree of continuous permafrost (Figure 4). In areas with sporadic permafrost, permafrost is found in patches or islands with temperatures below -2 °C. Areas with sporadic permafrost are typically in connection with peat, due to its insulating capability: If the peat is dry it insulates against heat from above and reduces thaw, while wet peat do not insulate.

In Greenland there is continuous permafrost in the northern part (dark purple in Figure 1), while to the south there is discontinuous, sporadic or even missing permafrost.

The permafrost zonation will likely change as a result of climate change with increasing temperatures, and it can be expected that the extent of continuous permafrost will decrease with increasing temperature, which will have consequences for the Arctic vegetation, hydrology and landscape (Walker et al., 2005).

Figure 4. Illustration of continuous, discontinuous and sporadic permafrost. North-south going vertical profile from Canada displaying decreased depth and breakup of permafrost towards the south. Notice the depth of the permafrost in the north end. Illustration from Brown (1970).



2.4 Arctic vegetation

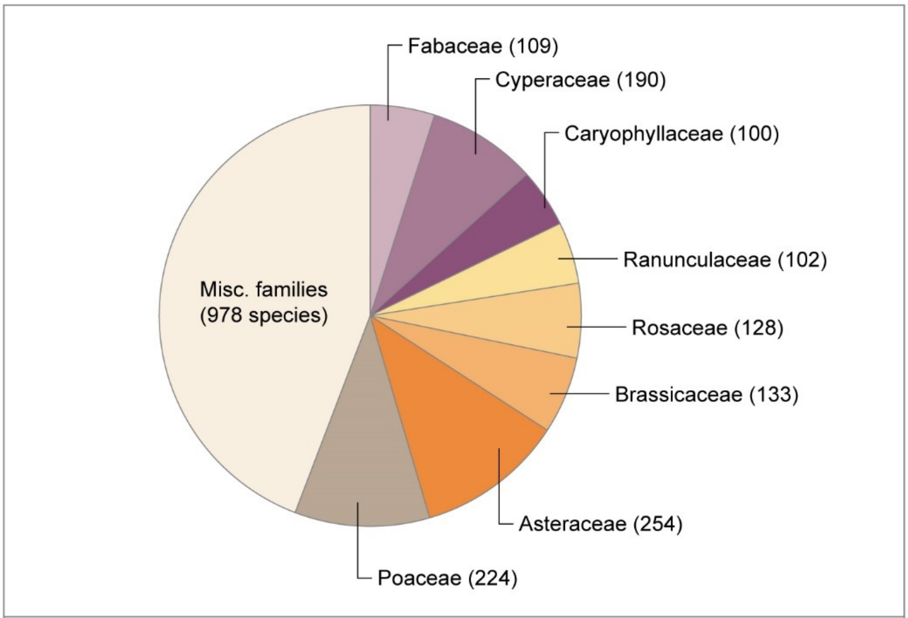
Arctic plant communities generally consist of much fewer species than is found at lower latitudes (Bilings and Mooney, 1968). They make up about 3% of the world's plant species (ACI-Assessment, 2005). These plant species migrated to the Arctic following the last glacial maximum extension of the ice sheets some 21,000 years ago and have therefore had little time to evolve to the extreme abiotic conditions of the Arctic environment. Many of the plant species survived the glacial period in refugia (Crawford et al., 1994, Bennike 2009). This allowed the best suited species to expand towards north and establish in the exposed soil as the ice retracted (Billings, 1992). Despite of the small number of vascular plant species the composition in individual vegetation plots (e.g. 1x1 m) has a similar or even higher diversity than found in boreal and temperate regions (ACI-Assessment, 2005). The Arctic plant species have multiple adaptations necessary to survive in the Arctic, an environment characterized by a number of restrictions for plant growth: low temperatures, a short growing season and nutrient depleted soil (see Table 1). The establishment of the present Arctic plant species following the last ice age was likely shaped by cold spells such as the Younger Dryas period (12,800 to 11,500 years ago) where many regions where re-glaciated and ice sheets re-expanded.

Table 1. Main restrictions for plant growth in the Arctic. Arctic species are adapted to the conditions listed in the table. (Based on Billings, 1987, Crawford, 1989, Giblin et al., 1991, Jonasson, 1997, Jonasson et al., 1999, Jonasson et al., 1996, Larcher, 1995, Semerdjieva et al., 2003, Shaver and Cutler, 1979, Ulrich and Gersper, 1978).

Low air and soil temperatures
Very short growing season
Encapsulation in snow or ice
Freezing
Limited availability of nutrients, due to slow decomposition
Drought
Nutrient buffer is in microbes during the growing season
Increased UV-B radiation
Permafrost and shallow active layer
Long-lasting snowdrifts
Flooding at thaw

Less than 1% of all vascular plant species occur in the Arctic and the species composition is much lower than at lower latitudes with an estimated total 2218 species in the entire Arctic region, of which 106 species are endemic (Daniëls et al., 2013). The vegetation is typically short and small in height and extension, and typically consists of dwarf bushes, grasses, perennial herbs, mosses and lichens. Very few annual herbs species are found in the Arctic, in Greenland for example only one. The species composition varies among sites and there are areas with a relatively high number of species, especially in wet lowlands at lower Arctic latitudes. Continuous vegetation is mainly found in the lowlands of Greenland, and in the high Arctic areas and at higher altitudes there are extensive areas almost without any vegetation of vascular plant and mosses. Here lichens prevail except for a few sturdy species such as for example from the *Saxifraga*, *Draba* and *Papaver* genera. Arctic plant species are typically perennial to accommodate the Arctic constraints, and they are all characterized by being able to survive freezing over extended periods; metabolize, grow, and reproduce at temperatures just above freezing. However, they grow slowly and may take many years to reach the reproductive stage because of the short growing season (Bilings and Mooney, 1968, Billings, 1987). Arctic woody or semi-wooded species for example grow with a rate of a few millimeters per year (Babb and Bliss, 1974) and actual trees are virtually absent, except for the sub-Arctic zone in southernmost Greenland. The growth rate itself is in some species higher than in temperate regions, however for a very short period of time, which shows an enzymatic adapted advantage to the very low temperatures, which means that the species during the growing season are more restricted by availability of nutrients, light if covered by snow (Cooper et al., 2011) and area of the green leaves for photosynthesis (because most Arctic plants are smaller than at lower latitudes), than the low temperature in itself (Chapin, 1983). Some species may even survive being buried under snow for 1½ years (Billings, 1987).

Arctic soils are generally nutrient deficient (Bilings and Mooney, 1968, Ulrich and Gersper, 1978) and the plants growing there respond to experimental addition of fertilizers by increasing the biomass both above and below ground (Jonasson et al., 1999). In general Arctic tundra plants minimize nutrient losses rather than having specialized structures for nutrient uptake, and they are able to store nutrients as well as to retract nutrients from dying parts of the plant and reuse them in new tissue (Berendse and Jonasson, 1992). One reason for the limitation of nutrients is that the source of nutrients – the decomposing organic material – is frozen during the majority of the year (Billings, 1987, Chapin, 1983) and then taken up by microbes when the soil thaws during spring (Jonasson et al., 1999). This means that nutrients released from dead organic material is mainly available during autumn (Jonasson et al., 1999) when the soil microbial populations decline and release their nutrient content (Giblin et al., 1991), but not during the growing season when the plants require nutrients to increase their biomass (Jonasson et al., 1996). The microbial biomass thus acts as a nutrient sink (Jonasson, 1997) and along with the nutrient deficient soil therefore restrict plant growth during the growing season. Arctic plants typically have a much enlarged root system to maximize uptake of nutrients available, where up to 95% of the plant's biomass can be below ground (Shaver and Cutler, 1979). Mycorrhizal symbionts are common aiding nutrient uptake (Michelsen et al., 1998), however the proportion of non-mychorrizial plant species increases towards the north (Olsson et al., 2004). Ectomycorrhizal symbionts form important associations with *Betula*, *Larix*, *Pinus*, *Salix*, *Dryas*, *Cassiope*, *Polygonum* and *Kobresia* in the Arctic (ACI-Assessment, 2005).



• Low diversity, species number less than 1% of the world flora
• 91 families, 430 genera, 2218 species
• Few gymnosperms, angiosperms represent 96% of the flora
• Low species diversity per family, with 8 species-rich families accounting for >50% of the flora (see above)
• Low species diversity per genus, with most species-rich genera *Carex* (152), *Salix* (72), *Oxytropis* (58), *Potentilla* (50), *Draba* (41), *Ranunculus* (40), *Papaver* (39), *Poa* (36), *Saxifraga* (35), *Artemisia* (33), *Puccinellia* (31), *Juncus* (30), *Pedicularis* (29), *Rumex* (28), *Astragalus* (28), *Silene* (24), *Erigeron* (24), *Luzula* (22) and *Eriophorum* (18)
• Around 5% endemic species, mainly Poaceae (24), Papaveraceae (15), Brassicaceae (15), Fabaceae (14) and Asteraceae (6), accounting for 70% of the endemic species flora
• Genera with relative high numbers of endemic species include *Papaver* (15), *Puccinellia* (13), *Oxytropis* (11), *Potentilla* (8) and *Draba* (8), accounting for 52% of the endemic species flora. Almost all are forbs or grasses, a few sedges, woody species absent
• Coherent with high percentage of circumpolar species
• High polyploidy (allopolyploidy) levels, in particular in the northern and longer glaciated areas
• Young with distinct phytogeographic history
• No strong influence by aliens
• Still native and with intact historical plant geography

Figure 5. Composition and characteristics of plant species in the Arctic. Figure copied from Daniëls et al. (2013).

Especially in the high Arctic, plant growth is considered water limited (Billings, 1987) because of the low precipitation level and low moisture content in the soil, if any soil is present (Gold and Bliss, 1995). The precipitation primarily arrives as snow and is available as surface run-off water during snowmelt before reaching rivers and being transported to sea. Snow patches may persist throughout summer delivering meltwater to the soil directly below the snow fan. Especially slopes may be limited in moisture during the growing season. Climate change with increasing temperatures in summer may cause changes in water availability and thereby change the species composition of the vegetation locally depending on the topography and availability of persisting snow fans. There are generally large differences in amount of precipitation from for example Southwest Greenland to high Arctic desserts (ACI-Assessment, 2005) and the plants living in these areas therefore also vary.

The Arctic landscape is a mosaic of microhabitats because the topography plays an important role in defining the local moisture content, temperature and insolation (Björn et al., 2004), and for example carbon content therefore also varies greatly even on the small scale (Jonasson et al., 2001). Plant species and vegetation cover in different microhabitats depend on these factors and vary with it. The topography even on a very small scale also determines the inclination of the sun on the plants and therefore also the available light for growth as well as the temperature in the plant that may vary with up to 25 ^{o}C across a cushion plant (for example *Dryas integrifolia*, *Saxifraga caespitosa*, *S. oppositifolia* and *Silene acaulis*) (Mølgaard, 1982). The temperature of a plant varies across its different parts and with its stature and composition. The better the coupling between the plant and the ground the better the plant can 'store' heat. Especially cushion plants can keep a positive temperature difference in relation to the surroundings at night and likely prolong enzymatic growth activity (Mølgaard, 1982).

2.5 Vegetation and permafrost

The vegetation protects the active layer against heat from the sun and surroundings and therefore insulates the permafrost from thawing during summer (Walker et al., 2003). The vegetation thus has profound significance for the stability of the permafrost layer, the depth of the active layer and the moisture content near the surface. If the insulating cover die or is torn off, the soil is exposed and stores heat, and the active layer increases (Lawson, 1986) and the water content decreases near the surface (Babb and Bliss, 1974). An intact vegetation cover and an organic crust is the key to maintaining the thermal balance between the active layer and the permafrost (Abele et al., 1984, Claridge and Mirza, 1981, Forbes et al., 2001, Jorgenson et al., 2015, Kevan, 1971, Lawson, 1986, Walker et al., 2003, Williams et al., 2013).

2.6 The natural Arctic terrain

Large parts of Greenland, where soil is present, is characterized by being underlain by permafrost, however in the southern parts it is discontinuous, sporadic or absent (Figure 1). The upper part of the permafrost that thaws every summer – the active layer – varies in depth from about 40 cm in Arctic deserts to 100 cm in wet areas depending on summer temperatures and soil type. The continuous dynamic cyclic processes of thaw and freeze affects the Arctic terrain mechanically and surface disturbances are characteristic of some Arctic soils. For example as polygon patterns due to slowly vertical and horizontal sorting of material over decades (Björn et al., 2004). Permafrost contains up to 50% excess ice and natural local melting events may also result in subsides and formation of thermokarst that may change run-off patterns and availability of water in an area (Bader and Guimond, 2004). Other natural mechanical processes that affects the terrain and landscape are spring flooding, erosion of riverbanks, slope processes, changes in river volumes for example due to extreme flooding events (melting of ice barriers of glacier lakes resulting in outburst floods) resulting in massive volume increases in rivers and flooding (Björn et al., 2004). Therefore, on a long time scale, physical or mechanical disruption of the soil and vegetation in the Arctic landscapes occur as part of the natural dynamics due to permafrost processes and spring runoff, and affects the colonization and survival of organisms and thus ecosystem development.

3 Damages to the vegetation cover

The Arctic vegetation is generally sensitive to physical and chemical stress (Table 1). The potential for quick revegetation and restored balance following disturbances is much reduced compared to lower latitudes. Arctic plant communities have limited resilience to physical damage, and disrupted vegetation, dead plants, removal of whole plants or just the green parts all reduces the vegetation's insulating capacity which may have significant adverse effects on the physical characteristics and thermal regime in the soil and permafrost (Figure 6).

Key factors for vegetation damages

Terrain	**Level**	Intersected/Varied topography
Active layer	**Frozen (hard top)**	Unfrozen top
Snow depth	**Deep**	Shallow
Snow density (packing/type)	**Densely windpacked**	Powder
Snow density	**High**	Low
Vegetation type	**Wet**	Dry
Flora species composition	**Common**	Rare
Vehicle ground pressure	**Low**	High
Vehicle path width	**Narrow**	Wide
Vehicle traction	**Rubber**	Steel

Increasing risk of vegetation damage →

Figure 6. Key factors for vegetation damages from physical activities such as drilling, seismic surveys or driving in the terrain. The green column signifies factors leading to a lower risk of vegetation damages, and the red column is factors leading to a higher risk of vegetation damages/more significant or permanent changes.

However, different areas in the Arctic (including Greenland) vary in sensitivity to disturbances from human activities depending on the species composition and soil potential. Areas with habitats holding rare species will for example be more sensitive to disturbances (seen from a biodiversity point-of-view) and may require special protection or mitigation and help to regenerate vegetative cover following disturbance. Less sensitive to disturbances are areas without vegetation, such as rock faces, gravel plains and wide shallow riverbeds, which are flooded every spring.

3.1 Vegetation damages and permafrost

A thick moss carpet and organic soil profile insulates the active layer against heat during summer, and therefore also the depth to which the water is able to drain (Walker et al., 2003). Removal of plants oppositely exposes the ground, reduces the albedo (Babb and Bliss, 1974) and increases the downward heat conduction leading to increased active layer and downward drainage (Abele et al., 1984, Walker et al., 2003). Human induced changes to the terrain can therefore accelerate and be much larger in areas with permafrost than in areas without permafrost and temperate regions.

The permafrost is stable as long as there is thermal balance, meaning that the yearly heat input is less than or equal to the heat loss. Any change in for example vegetation cover affecting the permafrost balance can cause the critical temperature threshold to be exceeded leading to a deeper active layer. Thawing of the permafrost leads to melting of excess ice with risk of accompanied subsidence and thermokarst (Felix and Raynolds, 1989a), and it is therefore very important to consider the risk of permafrost damage when planning activities on the Arctic tundra. In Arctic Canada for example, driving is not allowed within 150 m of a pingo (small ice cored hills) and building of roads are discouraged in areas of discontinuous permafrost (INAC, 2010). The vulnerability of an area with permafrost is directly proportional to its ice content in the ground (permafrost part) and inversely proportional to the average temperature of the ground (lves and Barry, 1974). Therefore, the more ice contained in the permafrost, the less stable the sediments are i.e. the larger the damages when the permafrost melts (Lawson, 1986). In an experimental study with intended driving on the summer tundra with six different types of off-road vehicles ranging in impact from an air-cushing vehicle (ACV, Hovercraft) over low pressure 'rolligons' to tracked 'weasels' and 'Nodwells', Abele and colleagues found that the active layer was increased with 4-6 cm compared to control sites even two years following the traffic on the vegetation (Abele et al., 1984). They ascribed this change primarily to the disrupted vegetation making it darker with lower albedo, decreasing its insulating abilities and thereby deepening the active layer. The degree to which the vegetation is disturbed of course depends on the specifications of the vehicles driving on the tundra. Using a Ranger 4WD and passing the same points sixty times during August in high Arctic Canada, Babb and Bliss (1974) only measured a 4-5 cm depression of the organic mat, but saw no changes in vegetative cover or thaw depths in the same year. In a longer-term study (minimum thirteen years), Kevan et al. (1995) examined effects on vegetation and active layer in tracks from tracked tractors with known ground pressure and number of passages. They found that overall, the vegetation cover was significantly reduced even after thirteen years. This was accompanied by a small, but significantly and unequivocally, increase in active layer in the tracks. The only exception was single drive ruts in wet sedge areas. Here the tracks were visible and water was running in them, but the vegetation cover was unchanged.

In a study from Alaska, Lawson (1986) examined the effect of one year of drilling activities at different sites. The study was performed thirty years following closure of the area. The study showed that destruction of the vegetative mat led to extensive and permanent (or at least three decades) changes in each site's physical characteristics and thermal regime. Light trampling and killing of plants resulted only in slightly modified thaw depths. Compaction of the vegetation and underlying soil mat led to increased depth of the active layer and affected the morphology of the terrain. Subsidence combined with erosion had created trails as deep as 5 m after 30 years. The results of that study indicate that the actual removal of the vegetation or surficial organic mat is critical to the extent that lasting physical modifications take place (Lawson, 1986). The Lawson study concluded that the degree of damage to an area from anthropogenic activities, primarily depends on the degree to which the thermal regime is changed, and secondly on wind and water erosion. Changes to the vegetative mat is the single most important parameter leading to changes in the thermal regime and causes the most dramatic and permanent changes to a site (Abele et al., 1984, Claridge and Mirza, 1981, Forbes et al., 2001, Jorgenson et al., 2015, Kevan, 1971, Lawson, 1986, Walker et al., 2003, Williams et al., 2013). Of other parameters, also vegetation type, volume and extent of ground ice, relief and geophysical composition of the ground determines the development of changes following vegetation damages (Lawson, 1986, Walker et al., 2003).

3.2 Dust, vegetation and permafrost

Dust may affect photosynthesis, respiration, transpiration and allow the penetration of phytotoxic gaseous pollutants. Visible injury symptoms may occur and generally there is decreased productivity. Most of the plant communities are affected by dust deposition so that community structure is altered (Farmer 1993). Myers-Smith et al. (2006) studied effects of the Dalton Highway, a 577 km long gravel road connecting the Prudhoe Bay Oilfield in Arctic Alaska with southern supply points. The highway was opened in 1975 and was built of quarried limestone bedrock and calcareous sedimentary deposits. The authors measured active layer depth, acidity, plant species composition between 2 and 800 m downwind from the gravel road. The study documented effects of wind and trucks moving highway dust onto living plants limiting light for growth, increasing the pH of the soil and the active layer depth, while decreasing the soil organic matter content and shifting the plant species composition towards primarily graminoids over a thirteen years period (Myers-Smith et al., 2006). Their sampling regime did not allow for determining the exact maximum disturbance range, but the effect was wider for the plant community changes, which was observed more than 100 m from the gravel road. One explanation for the increased thaw depth was that dust also settles on the snow leading to long-term reduced albedo and hence snow pack depth. The authors assumed a 200 m disturbed zone on either site of the road, leading to a total impact of a 115 km^2 disturbed area (Myers-Smith et al., 2006). Other studies have found similar impacts from dust on vegetation composition, acidity and active layer depths (Walker and Everett, 1987, Farmer, 1993, Auerbach et al., 1997, Gill et al., 2014). Effects of construction of gravel roads in the Arctic, even intended for short time use, should be assessed seriously with respect to long-term consequences of a new development or project.

3.3 Oil spill, vegetation and permafrost

Oil spills cause vegetation die-off and increases in thaw depth, where severity depends on oil type and amount of oil, as well as on vegetation and soil type, moisture content etc. Risks of oil spills are therefore important to consider in the context of anthropogenic activities in the Arctic, as the negative consequences for the vegetation are long-lasting and causes changes in the active layer as well.

In a three-year Low Arctic artificial oil spill study, where there was permafrost in the study sites, a large experimental crude oil spill was created to study the effects on the active layer (Seburn and Kershaw, 1997). The study took place at three experimental sites: 1) Undisturbed black spruce forest (*Picea mariana)*, 2) black spruce forest cleared with intact organic mat, and 3) a severely disturbed site simulating buried pipeline trench. To mimic a below ground pipeline rupture, 3273 L of crude oil was pumped into the ground over 24 h. The oil saturated the ground and seeped to the surface and eventually covered 670 m^2. At each of the spill sites similar control and impact sites were appointed following the spill (total n=349). The study showed that there were large differences in active layer depth between oiled and control sites. In each of the three consecutive study years, the mean annual thaw depth of the active layer was 130% deeper at the oily sites in type 1) forest, however the deepest active layer was found in oiled type 2) sites where the vegetation had been cleared off. However, after three years the active layer was significantly deeper at the oily type 3) sites, showing that an oil spill can affect the temperature even deeper than 150 cm. The reason for the changes in depth of active layer were explained by decreased albedo by either die-off of the vegetation canopy, mosses soaked with oil and the dark oily soil itself. Further, the oil in the surface acted as a heat conductor leading heat down into the ground (Seburn and Kershaw, 1997). These study sites have not been reported revisited later, however other studies (next paragraph) have found much longer lasting effects from oil spills.

Collins et al. (1994) looked at effects to the vegetation, active layer and ground fifteen years following an experimental oil spill in subarctic Alaska in an area with permafrost. The experimental set-up is explained in detail in previous publications on the same experimental oil spill (Jenkins et al., 1978, Johnson, 1980, Sparrow et al., 1978): In both summer and winter 7600 L crude oil was 'spilled' at each of two different sites. In winter, the oil seeped below the snow on the surface of the frozen ground, entering ground in the spring as the active layer melted. It covered 188 m^2 after snowmelt. In summer, the oil flowed into the organic crust and spread downslope and covered 303 m^2. Following two years, 40% of the winter area had oil on the surface opposed to only 10% of the summer area. Three years following the oil spills, the depths of the active layer had increased by a mean of 13 cm with respect to control sites. Six years after the oil spill, the depth of the active layer thaw was still increasing. Fifteen years following the spill the depth of the active layer had increased from the control reference of 57 cm in 1978 to almost 200 cm in 1991 in the winter spill area. In the summer spill area active layer depth had more or less stabilized from 1982 onwards. The differences between summer and winter oil spills were explained by two mechanisms: 1) in winter the oil stayed on the ground below the snow and therefore more oil was left on the ground over time. In summer the oil immediately began to penetrate the ground. 2) This gave differences in albedo for the summer and winter sites, where oil on the surface and dead vegetation had the lowest albedo and were more dominant in the winter sites. However, also the reduced isolative capacity of dead moss to prevent heat flux is given a general explanatory power. Further, when the ground thaw oil penetrates and changes the thermal regime leading heat into the ground, augmenting the melt. Especially in the winter oil spill area, the deeper active layer was associated with subsidences up to 60 cm deep. Therefore, the total effect of an oil spill on the active layer is calculated as the increased thaw depth + subsidence. In some places in the winter oil spill area, the combined effect was up to 300 cm after fifteen years (Collins et al., 1994). From this study it appears that everything but cotton-grass tussocks (*Eriophorum vaginatum*) dies almost immediately or within a few years, and after fifteen years there was no real regrowth of shrubs in surface oiled areas. However, *E. vaginatum* actually grew vigorously following the oil spill. This was explained by relaxed competition by eliminating the shading from shrubs, as well as by the raised growth form of *E. vaginatum* that in itself may protect it against oil on the surface. Its annual root growth also appears advantageous since the roots penetrate the polluted soil and reach below the polluted topsoil. The study concluded that the winter oil spill overall caused greater damages to vegetation, thaw depth and substrate than did the summer spill (Collins et al., 1994).

Both of the above studies (Collins et al., 1994, Seburn and Kershaw, 1997) took place in subarctic Alaska with discontinuous permafrost and where the temperature of the permafrost was around 1 ^{o}C at the transition between ice and active layer. However, in another subarctic experimental oil spill site in Canada, they found no effect on the depth of the active layer, regardless of whether the oil was deployed in winter or summer (Wein and Bliss, 1973). Whether this was related to oil type (they used light gravity sweet crude oil), soil type or amount of oil applied is unfortunately not clear. One possible explanation could be that the plots of the Wein and Bliss study generally were very moist and already saturated at the base of the active layer when the oil was applied, which reduced the effect on the vegetation.

In High Arctic Greenland an oil spill study was conducted in Jameson Land in the 1980ies (Holt, 1987). The study examined effect on the vegetation and did not look at effects on the active layer. Here, either 10 L crude oil or diesel oil was applied to plots of 1 m^2, and the effect on the vegetation was in the first report measured over a three year period. The study found that the oil had an immediate and lethal effect: within one week of the oil spill the vegetation began to wilt and die. The lethality related oppositely to moisture content in the soil. This was explained by wet areas having a water-logged surface that repels the oil. Therefore, plants with root system extending below the water-oil interphase have a better chance of surviving an oil spill, as well as regrowth begins faster as the roots can replenish the plant above ground. As proposed by Johnson (1980), Holt (1987) also suggested that a vertical rooting strategy as opposed to a shallow root system makes a species less sensitive to oil spill, because it minimizes the amount of biomass that comes in to direct contact with the oil. Plants with vertical roots are for example grasses. The effect of an oil spill will therefore also depend on whether the oil penetrates into the ground or remains on the surface. In the Holt study, the areas least susceptible to oil spills, regardless of oil type, were wet graminoid marshes with *Salix* and *Carex* spp. Oppositely, dry dwarf shrub heaths were especially susceptible to oil spills with a reduction in plant cover to a few percent and very little total vegetative recovery was observed (Bay 1997), only 2% recovery in the third year for crude oil and no recovery at all for diesel oil. In general, the effect of diesel oil was more pronounced than for crude oil, which has also been found elsewhere (Walker et al., 1978). None of the plots polluted by Holt (1987) saw recovery of forbs, whereas mosses and sedges began to recover within the three year study period. In fact secondary effects appeared as some species of forbs died in the second year, which was explained by the harsh winters having a greater effect on the weakened plants (Holt, 1987). Overall, the total plant regrowth was in all but the marsh and wet grass land plots less than 10% in year three. The shrub that showed the greatest ability for recovery was *Salix arctica* (Holt, 1987). Similar accelerated growth was also observed for *Salix* spp. and *Betula* spp. by Wein and Bliss (1973) following an experimental oil spill and was suggested explained by "…reduced competition for nutrients by the reduced photosynthetic surface or from a greater availability of nutrients resulting from accelerated decomposition" (of the dead plants). The hypothesis of accelerated decomposition was unsupported in the Holt study, but Johnson (1980) did measure increased bacterial activity following another experimental oil spill in the subarctic. The Holt (1987) study concluded that also exposure to secondary stressors at exposed sites will reduce regrowth, as well as oil on the surface of the soil may prevent or reduce establishment of seedlings.

The study sites of Holt (1987) was revisited eleven years after the oil spill. Here, the composition of the vegetation and cover was analyzed in all plots (Bay, 1997). Interestingly, the regrowth of shrubs, herbs and graminoids were still very insignificant with less than 1% cover in all plots (Table 2). In opposition to other studies (Johnson, 1980, Walker et al., 1987, Walker et al., 1978), mosses were in the studies performed by Holt (1987) and Bay (1997) found to recover and recolonize relatively fast and efficient.

Table 2. Coverage of different plant groups (%) in the different plant communities before and eleven years after experimental oil spills of crude or diesel oil. Number of species in 1993 not occurring in the undisturbed vegetation is also given. Less than 1% cover is indicated as +. Notice how only mosses especially in wet areas show signs of recovery during the eleven year study period. Table copied from Bay (1997).

Diesel oil	Woody plants		Forbs		Graminoids		Mosses		Lichens		No. of vasc. spp.		No. of new vasc. spp.
Plant community	1982	1993	1982	1993	1982	1993	1982	1993	1982	1993	1982	1993	in 1993
Dry *Dryas-Cassiope* heath	47	0	+	0	+	+	1	+	3	+	7	1	0
Dry *Cassiope* heath	33	0	1	0	0	0	37	1	8	+	10	1	0
Moist *Vaccinium* heath	27	0	11	0	3	+	60	6	0	0	13	2	3
Moist grassland	1	0	1	+	41	2	76	22	0	0	15	8	1
Wet fen	10	0	2	0	11	+	100	53	0	0	5	1	3

Crude oil	Woody plants		Forbs		Graminoids		Mosses		Lichens		No. of vasc. spp.		No. of new vasc. spp.
Plant community	1982	1993	1982	1993	1982	1993	1982	1993	1982	1993	1982	1993	in 1993
Dry *Dryas-Cassiope* heath	24	+	+	+	+	+	4	+	6	+	12	4	1
Dry *Cassiope* heath	31	4	+	0	+	0	30	+	1	+	4	1	0
Moist *Vaccinium* heath	19	0	18	0	8	+	67	3	0	0	14	4	2
Moist grassland	1	+	1	0	43	3	73	20	0	0	10	7	1
Wet fen	18	+	2	0	5	+	100	70	0	0	5	3	2

As has been documented previously, wet areas aid survival during an oil spill, explained by the minimized contact between underground plant-parts and oil in water-logged or saturated areas. As none of the other plant groups really saw any recovery over the eleven year study period, most regrowth was observed in wet areas naturally favored by mosses. After eleven years the moss cover in wet fens increased to 53% and 70% of the original cover before the experimental spills of diesel and crude oil, respectively. The die-off of mosses was, however, also high with a moss coverage of only 5% and 17%, respectively in the first year after the spills (Holt, 1987).

The study sites and plots treated with crude oil and diesel oil spill in 1982 were revisited again in 2014 where in addition soil samples were collected for analyses of residual concentration of oil components in the soil (Kim Gustavson, unpublished data). Inspection of the experimental plots in 2014 indicated that major effects of the spill in 1982 still persisted on the vegetation cover on the following plant communities: *Extreme dry dwarf-shrub, moist dwarf-shrub* and *dry dwarf-shrub*. Photos of the plots taken at the inspection in 2014 is shown in Figures 7a-c (P. Aastrup, unpublished data). Vegetation cover was recovered somewhat in the plant communities: *Wet marsh* and *moist meadow*. Walker et al. (1978) showed crude oil to be less phytotoxic than diesel oil on the different plant species tested, however the inspection in 2014 indicated that spill of crude oil may also have long lasting effects on vegetation cover in Arctic areas as the re-growth was sparse.

Holt (1987) and Wein and Bliss (1973) indicated that *Salix* spp. had a high potential for recovery, however, further studies in the same area as Holt's study in Greenland showed that the damages seemed to worsen over a few years following the application of oil (Bay, 1997). The studies performed by Holt (1987) in fact indicate that oil spill may have distinct and long-term (over several decades of years) impacts (mainly reduced plant cover and reduced number of species) on plants and vegetation in Arctic areas. The impact is most pronounced on vegetation on dry soil.

Results for the residual concentration of oil components in soil from the plots treated with crude oil or diesel oil in 1982 is shown in Figure 8. The results indicate a still high concentration of residual crude oil components in the soil in 2014 more than 30 years following the experimental spill on the plots. In comparison the concentration of residual oil components in plots treated with diesel oil was low or below detection limits. Concentration in reference plots was very low (see legend to Figure 7).

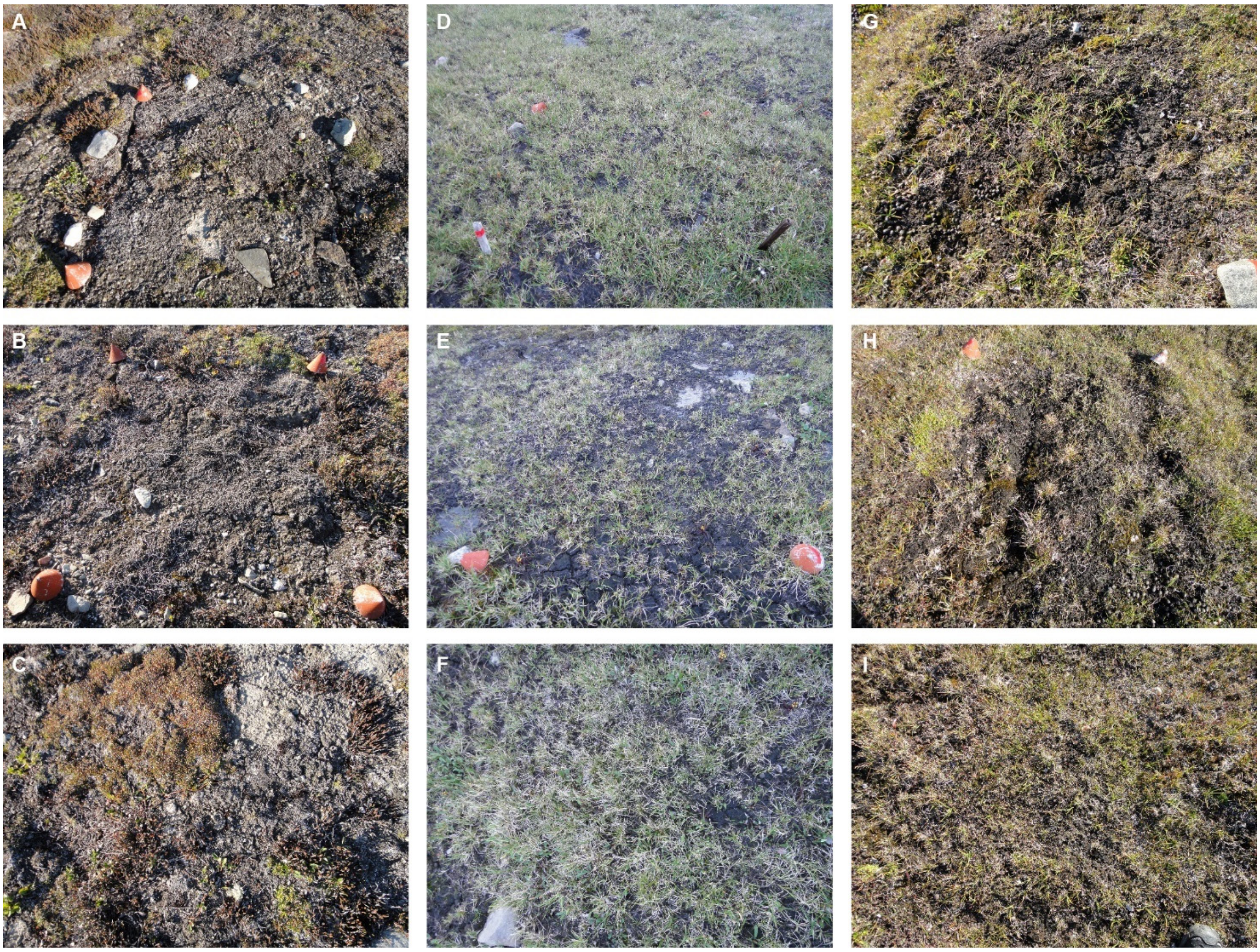


Figure 7. Examples of the plots exposed to crude oil (top) and diesel oil (middle) in 1982 (Holt 1987) compared to an untreated control plot (bottom), all photographed in 2014. Photo A,B and C show plots from 'extreme dry dwarf shrub' plant community type. Photo D,E and F show plots from moist meadow community type and photos G, H and I from moist dwarf shrub heath. Original non-published data.

In summary, these long-term studies demonstrate that effects of oil spills in the Arctic need long-term evaluation ideally over a period of more than thirty years to examine true effects on the vegetation and even longer to examine degradation of the oil itself. This is likely related to the slow growth rate of vegetation and on the general limited turn-over rate and slow oil degradation rate by microorganisms.

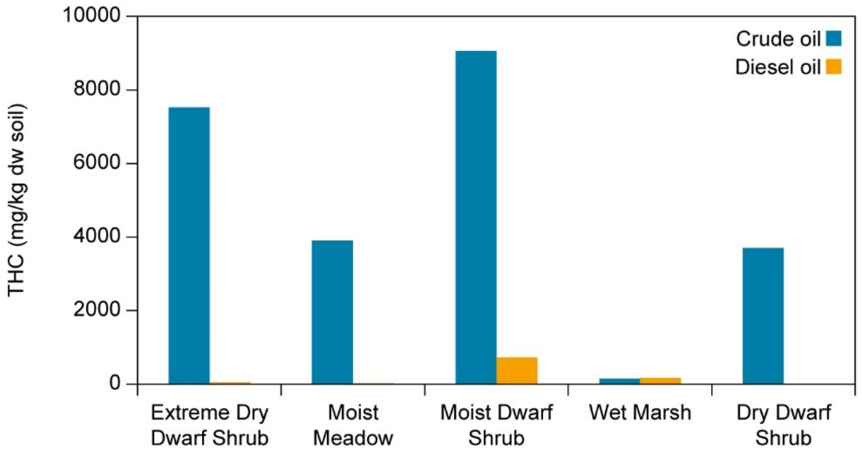


Figure 8. Concentration of oil residues in soil sampled in the Holt (1987) plots in 2014 more that 30 years after the experimental spill in 1982. Original non-published data. THC = Total Hydrocarbons. The concentrations in the reference plots (n = 10) was in average 22.7 mg THC/kg dw (sd. dev 4.7 mg/kg). The initial THC concentration is estimated at about 30,000 mg/kg dw soil.

In general severity of effects of oil on the vegetation have in experimental set-ups been found to depend on:

- moisture content of the soil; the more saturated the soil is, the less the impact and the faster the regrowth (Bay, 1997, Holt, 1987, Walker et al., 1978),
- upright growth form and a vertical root system of a species, as well as underground storage organs favors survival during oil spills (Holt, 1987, Johnson, 1980),
- type and amount of oil, where refined oil products are more destructive than crude oil (Walker et al., 1978),
- the degree to which oil penetrates in to the organic crust (Johnson, 1980, Walker et al., 1978),
- degradation rate of the oil; the slower the rate the longer lasting the effect is (Holt, 1987),
- season of the oil spill (Collins et al., 1994, Johnson, 1980, Wein and Bliss, 1973), with spills in winter being more severe,
- degree of secondary stressors such as snow abrasion, frost, draught, herbivores (Holt, 1987).

3.4 Thermokarst

Damage and removal of the vegetation can lead to damages with wider effects because it changes the thermal balance as introduced above. When the soil is exposed during vegetation die-offs, it stores heat and the permafrost melts. Thermokarsts are depressions created in areas where permafrost containing excess ice melts (Raynolds et al., 2014). Formation of thermokarst can be a natural process, but is often caused by human activities impacting the vegetation and top soil. Because permafrost contains up to 50 % excess ice, melting hereof leaves holes in the soil, which changes the underground run-off pattern and can lead to removal of soil with the meltwater. When the soil is removed below the surface due to the melting permafrost ice, underground drainage systems are created. At a certain point the remaining top soil can no longer support the weight of the surface and it collapses, leaving a compression / hole in the landscape (Figure 9) (Bader and Guimond, 2004).

Figure 9. A thermokarst area in the Arctic landscape. Thermokarsts are created in areas where the permafrost layer thaws, because permafrost contains up to 50% ice. When the ice melts the melt water runs off and carries soil with it. When soil is removed below the surface, underground drainage systems are created. At a certain point the remaining top soil can no longer support the weight of the surface and it collapses, leaving a depression/hole in the landscape, i.e. a thermokarst. Thermokarsts may expand because the meltwater will intrude deeper into the ground carrying heat and accelerating the thaw. Photo: David Boertmann

The shape of the ice in the permafrost as well as the structure of the soil determines the appearance of the thermokarst. After initial melting the structure of the material determines how stable the new situation is: More coarse materials such as sand and gravel are better stabilizers than fine grained sediments such as clay and silt. Saturated clay and silt easily destabilize and begins to move away (Claridge and Mirza, 1981). The process leading to thermokarst also depends on hydrology; the better the drainage the greater the effect and the faster the thermokarst evolves. Downstream from a thermokarst run-off may continue above ground leading to small rivers and also erosion. Furthermore, the thawed soil can lead to changes in the hydrology due to the melting of stored ice and therefore intrusion of surface water. Even a small subsidence can expand substantially along the margins: If water begins to pool in the depression, the thermokarst will usually accelerate due to the efficient thermoconductive properties of water combined with water's ability to penetrate deep into any permafrost crack: Intruding water will increase the temperature and accelerate the permafrost thaw (Bader and Guimond, 2004). In areas with discontinuous permafrost, linear seismic lines for example, have the potential to completely remove permafrost and therefore change the overlaying land cover type over time (Williams et al., 2013). The lack of regeneration of permafrost in this type of environment is due to a positive feedback between subsides and intruding water that prevents the top layer (active layer) from being water unsaturated which is required to maintain permafrost (Jorgenson et al., 2010b, Williams et al., 2013). It is therefore essential to consider and prevent potential impacts on the permafrost from various human activities on the Arctic vegetation.

A study from Alaska showed that an entire well site (East Oumalik), used only for a single year was completely destroyed by thermokarsting over a thirty year period following closure of the site. Further, the thermokarsting was not restricted to the drill site but expanded into areas that were not even used originally, but laid adjacent to the drill area during the one year of drilling activities (Lawson, 1986) (Figure 10). This is one of the most horrific expamles of damages caused by the earliest exploration for oil and gas in 1950ies. The damages were caused by either trampling of vegetation, killing the vegetative cover, removal of the vegetative mat, or removal of the vegetation and soil, which changes the thermic propoerties of the ground underneath.

Disturbances to the soil

Compression of the soil and / or organic mat can lead to changes of the soil conditions, especially in areas with permafrost (Claridge and Mirza, 1981). Stability, temperature, oxygen, nutrient and water content may for example be altered from driving in the terrain. When the active layer is compressed it loses its insulating capacity leading to a greater downward conduction of heat during summer (Babb and Bliss, 1974). If compression reduces the drainage of the soil, water will accumulate on the surface augmenting the warming of the soil (Claridge and Mirza, 1981). This can increase the depth of the active layer, however to a lesser degree than by removal of the vegetation. Standing water hinders regrowth of destroyed vegetation (Abele et al., 1984) and compression of the active layer may lead to subsidence and thermokarsting (Claridge and Mirza, 1981), especially if the surface organic matter is removed, since the organic matter acts as a heat insulator for the underlying layers (Abele et al., 1984, Felix and Raynolds, 1989a, Haag and Bliss, 1974). The process of disruption can therefore easily accelerate. Canada has special regulation for travelling on the tundra to reduce the risk of subsidence, and winter roads created of snow and ice on top of frozen ground are required to protect the permafrost (INAC, 2010).

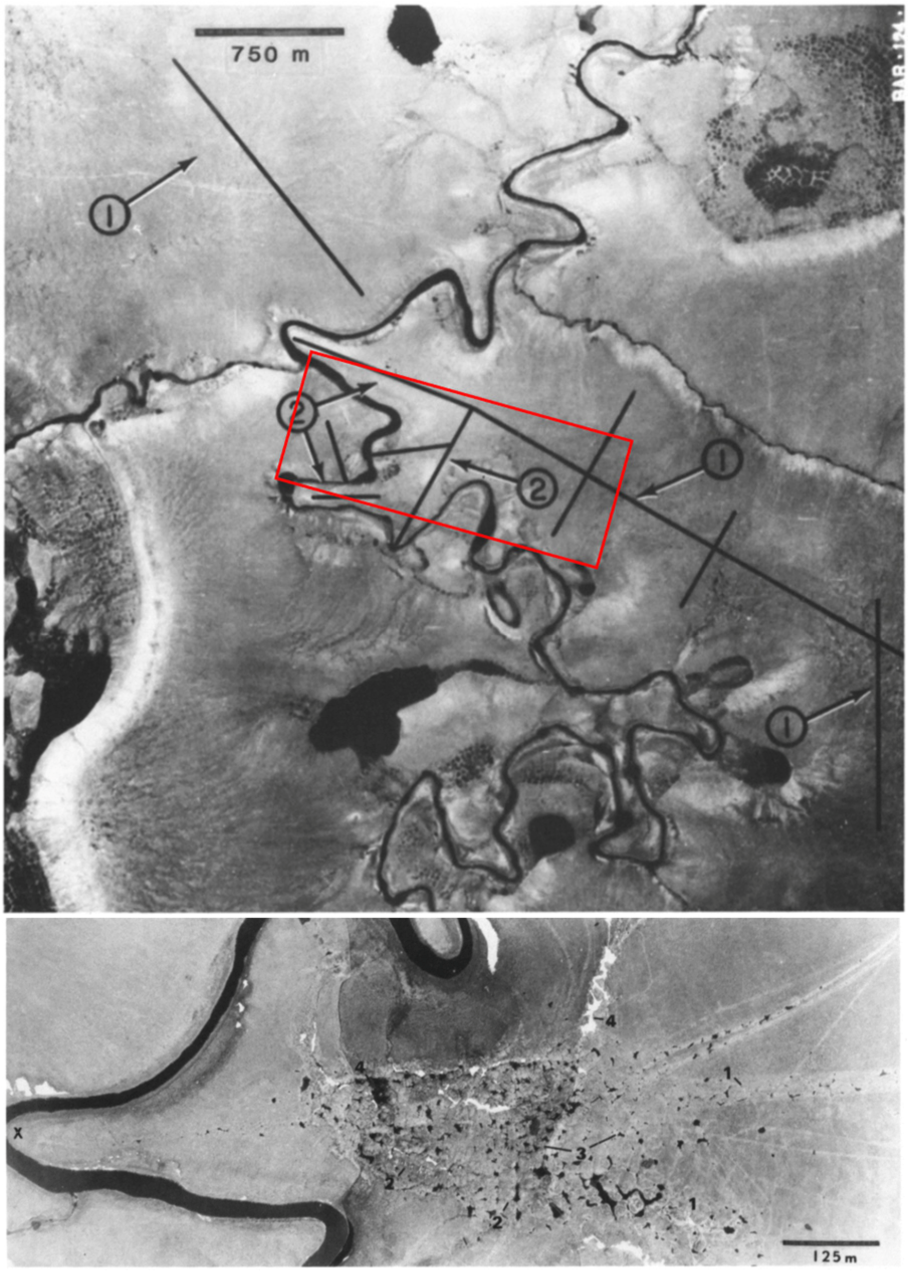


Figure 10. Example of area destroyed by thermokarst following oil exploration. Upper picture: Aerial photo (1949) of the area before drilling began in 1951. Drilling and construction took place over a full year. The lines indicate drilling transects. Lower picture: Aerial photo of part of the area (red frame) following the year of drilling activity. The cross on the lower picture denotes the end of the long transect line shown in the upper picture. The black areas in the lower picture are thermokarsts. Note all the vehicle tracks visible after thirty years. Photos are from (Lawson, 1986)

Especially peatlands are protected and special instructions exists for building winter roads to avoid subsidence. The regulation works so well that no subsidence's were observed in a large study examining effects of multi-year winter roads in Hudson Bay, Canada (Campbell and Bergeron, 2012). Oppositely, the first experiences with terrestrial seismic surveys in 1984, Jameson Land, Greenland, are still visible on the Arctic tundra, because the dwarf-shrub heath was killed or removed by the seismic trucks (Forbes et al., 2001, Hansen et al., 2012), see also Chapter 7.3.

A weak/limited compression does not lead to long-term or permanent physical changes (Lawson, 1986). Actually, a slight disturbance to the vegetation or soil for example a single track on the tundra, where the organic layer and vegetation remains intact, may lead to an increase in turnover and plant growth (Abele et al., 1984), likely caused by increased soil water, increased temperature and nutrient movement. The increase in nutrients results from compression of the standing dead vegetation bringing it into contact with soil microbes leading to accelerated decomposition and nutrient release (Chapin and Shaver, 1981). However, when measured over a +10-year period the species composition did change in tracks compared to controls to consist primarily of graminoids as opposed to shrubs and forbs (Chapin and Shaver, 1981).

Driving in early fall may result in driving on snow over unfrozen ground, which compacts the snow, reducing its insulation capacity and allowing the ground to freeze harder and deeper more quickly. This will reduce the depth of the active layer the following summer because the active layer froze harder during winter due to compression from the vehicles (Bader and Guimond, 2004). This again feeds back to the vegetation where reduced summer temperatures in the ground hampers availability of nutrients for plant growth.

The compression of the soil and the increased active layer also results in an increased greenhouse gas release from the nitrous oxide, methane and CO_2, otherwise stored in the permafrost (Billings, 1987, Elberling et al., 2010).

The resulting changes to an area do not stop to develop until a new equilibrium has been reached in terms of a constant depth of the active layer (Babb and Bliss, 1974). For example, compression or disruption of an area with ice-rich silt produces thaw sediment with little structure prolonging the thawing process, and the thaw depth will keep increasing until a sufficiently thick insulating layer of sediment has been build up (Lawson, 1986). Subsequent growth of vegetation and an increasing mat of organic matter aids maintaining the new equilibrium. When thawing is finally reduced, so is the production of meltwater and the potential for erosion, and the site will gradually reach a new equilibrium (Babb and Bliss, 1974, Lawson, 1986) after which the vegetation can establish more permanently.

3.5 Effects of vegetation disturbances on hydrology and erosion

Erosion is a natural process of withering and degradation supported by wind and water over thousands of years, however *accelerated erosion* is the term used for a human-caused increase in the rate of erosion that occurs when man alters the natural system by various land use practices. The rate of erosion is affected by numerous processes and qualities of an area where soil properties, vegetation coverage, temperature, drainage and relief are the most important. Hydraulic and thermal erosion are the two primary processes (Claridge and Mirza, 1981). Rainfall and surface run-off, for example melt water, can cause detachment and transport of soil particles (Babb and Bliss, 1974). Once thawing of permafrost and erosion has begun, the process is difficult to stop, even over years (Claridge and Mirza, 1981, Kevan et al., 1995). One reason for this is the lack of vegetation in the eroded area to stop the thermal erosion process. The susceptibility of an area to hydraulic erosion depends on the soil properties (Table 3), flow velocity and slope. Silt and fine-grained sand are most easily eroded due to the lack of cohesion in this substrate. Thermal erosion on the other hand is driven by a process of rapid thawing of ice-filled soil, for example permafrost, consisting of fine-grained material. It may result from human activities leading to removal of the vegetation and / or organic mat, changed drainage or excavations. Thawing of fine-grained soils with little cohesion easily results in mass-movement of soil matter. The thermal regime of such an area is therefore very sensitive to changes in drainage pattern, water build-up and channelizing run-off, as this may all change the thermal balance of an area with permafrost (Claridge and Mirza, 1981). Removal of vegetation and the corresponding increase in active layer thickness can therefore lead to changes in run-off patterns, because it allows a free flow of water as opposed water in a frozen condition. The compressions left in the ground by vehicles can lead water to the surface because the upper most compressed organic crust otherwise has the highest capacity to conduct water. The lower hydraulic conductivity of the organic mat therefore leaves the tracks as drainage systems filling with water during snow melt (Claridge and Mirza, 1981), and may hinder water flow to areas below the intersecting trail (Forbes, 1998, Kevan et al., 1995). If the run-off increases drastically for example during spring and summer or in periods with rain, the increased run-off along certain paths can lead to thermokarst (see chapter 3.4), erosion and subsidence. Thermokarst persists in the landscape and can change the run-off above ground as well, as the underwater drainage system may continue above ground downstream from the thermokarst for example creating small rivers in spring. The changed hydrology alters the amount of plant-available water in the ground and can therefore, over time, change the composition of plants in the area (Kevan et al., 1995, Williams et al., 2013). What seems as a simple effect on the terrain such as a track may therefore have long lasting consequences for the plant community, hydrology and aesthetic impression of the terrain.

Table 3. Overview of different soil substrates' potential for erosion. Modified from Claridge and Mirza (1981)

Soil description	General charateristics	Erosion potential
Clean sand and gravel with little or no fines (< 7% silt and clay)	Free-draining. Medium to high density, occurs in frozen and unfrozen states, massive ice inclusions are uncommon	Very low to nil
Silty sand and gravel, mixture of clay, silt, sand and gravel or cobbles and boulders. Fine-grained material < 50%	Found in frozen and unfrozen soils. Massive ice inclusions may be encountered especially in colluvial deposits.	Low to medium depending upon thermal conditions, topography and hydrology
Sandy or gravelly silt or clay. Fine grained material >50%	Either frozen or unfrozen. High ice content or massive ice segregation common	Moderate to high
Silt - organic and inorganic silt and clayey silt	Occurs in frozen or unfrozen state. High ice content common in frozen silt	High
Clay or silty clay	Varies in moisture content, in-place density and colour	Moderate to high
Peat and organic matters	High moisture, low density	Low to medium, depending upon silt content
Bedrock, unweathered		Non-erodible

In the study by Kevan et al. (1995) (see above in Chapter 3.1) subsidence associated with almost all ruts was also found. In a more wet area, described as 'wet and marshy ground', the ruts had grown twenty cm deep and water flew continuously serving as drainage from up-slope areas and the flowing water caused chronic, small-scale erosion yearly, as it is diverted down these channels. Subsidence was especially pronounced where tracks crossed ice wedges in dry habitats because it led to evaporation of melting ice from the perennially wet surface. The exposed surface of the disturbed / killed vegetation reduced the albedo and heated up, accelerating water-loss and leading to subsidence. In wet areas subsidence was instead explained as the direct effect of compacting the vegetation mat and soil (Kevan et al., 1995). The authors saw ruts crossing perpendicular to the slope of a marshy sedge meadow leading to drainage of areas downslope from the rut preventing the vegetation there from getting water from the snowmelt in spring, which is otherwise the primary source of water in the High Arctic. Despite that these ruts had only been driven eight times in total the associated changes in hydrology led to changes in the vegetative species composition downslope from the ruts even thirteen years later. Similar effects of ruts have also been observed in other studies (Forbes, 1998). It is evident that detailed planning on how, where and when to drive on the Arctic tundra is essential in order to avoid or minimize disturbance of vegetation, hydrology, permafrost and aesthetic appearance.

3.6 Effects of disturbances to species composition

The depth of a surface compression following traffic is a good indicator of the extent of damage done to the vegetation (Abele et al., 1984). Following disturbances to the vegetation some species grow faster and recover more quickly, for example sedges and mosses in wet areas. Other species grow very slowly and may not recover from the wear of for example seismic trucks. These are typically dwarf-shrub species in dry areas such as *Cassiope*, *Arctostaphylos*, *Empetrum*, *Betula* and *Rhododendron*. Killing of species of these genera in dry heaths are visible in the terrain as tracks or scars left for decades (Hansen et al., 2012, Wegeberg and Boertmann, 2016). As is indicated, the primary restrictor for regrowth of disturbed areas in especially High Arctic areas is the amount of available water. Typically wet marshes recover much faster than dry areas, although possibly with changes to the composition of the vegetation. Together with the hydrological changes described above, tracks, from heavy trucks for example, may lead to regrowth of new and opportunistic species for which the altered conditions may be more optimal. This will change the plant community in the area for a long period of time if not permanently (Table 4). There are examples of single-pass tracks laid perpendicular to water run-off, leading to drainage of wetlands and changing the area for decades (Forbes, 1998). Anthropogenic activities may therefore scar the landscape for decades, if not permanently, leaving tracks, drained areas and bare soil and by changing the vegetation cover over time, as the original vegetation may suffer great changes and potentially lead to new plant communities in the area (Lawson, 1986).

Table 4. Medium-term (20-75 years) response pattern of Arctic vegetation from five main disturbance types. W = wet, M = moist, D = dry. 1 = less than control, 2 = equal to control, 3 = higher than control. A dash – indicates no data. Data are based on studies in Arctic Alaska, Canada, Greenland and Russia. From Forbes et al. (2001).

	Organic layer removal						*Mounds of soil and organic matter*			*Housing*						*Vehicle tracks*						*Trampling*					
	partial			*total*						*ancient*			*modern*			*single pass*			*multi-pass*			*light*			*heavy*		
Responses	*W*	*M*	*D*	*W*	*M*	*D*	*W*	*M*	*D*	*W*	*M*	*D*	*W*	*M*	*D*	*W*	*M*	*D*	*W*	*M*	*D*	*W*	*M*	*D*	*W*	*M*	*D*
Total cover	2-3	2-3	—	2	1-2	1	—	2	—	—	3	2-3	—	2-3	1	2	2	1-2	2	1-2	1	2	2	1-2	2	2-3	1
Vascular cover	1-2	1-2	1	1-2	1-2	1	—	2	—	—	3	2-3	—	3	1	2	2-3	1-2	2	1-3	1	2	2	1-2	2	1-3	1
Vascular biomass	1-2	1	1	1-2	1	1	—	2-3	—	—	3	3	—	3	1	2	1-2	1-2	2	1-3	1	2	2	1-2	2	1-3	1
Species richness	1-3	1-3	1-2	1-2	1-2	1	—	1-3	—	—	1-3	3	—	1	1	2	1-3	1	1-2	1-2	1	2	1	1-2	1	1	1
Height	2-3	2-3	1-2	2	1-2	1	—	2-3	—	—	2-3	2-3	—	3	1	2	2	1-2	2	1-3	1	2	1-2	1-2	2	1-3	1

3.7 Effects on rare plants and vegetation

The distribution of some rare plant species can be extremely restricted and their numbers at the few sites can be very few. In Greenland such species are red-listed (Boertmann & Bay 2018). Depending on the population size such population are very sensitive to habitat destruction, and entire populations can be wiped out by a single activity. General and regional information about the distribution of these red listed species can be found in literature (e.g. Bay, 1992, Feilberg, 1984, Fredskild, 1995, Halliday and Corner, 2019), but thorough botanical background studies and planning of the operations and placement infrastructure are essential to protect such species.

4 Activities leading to vegetation damages

There are many different human activities that leads to vegetation damages and mitigation techniques should be outlined during the planning stage of anthropogenic activities to minimize potential environmental impacts. Oil spills (Bay, 1997, Collins et al., 1994, Council, 2003, Holt, 1987, Jorgenson and Joyce, 1994, McKendrick and Mitchell, 1978), roads (Campbell and Bergeron, 2012, Claridge and Mirza, 1981, Gill et al., 2014, Head, 2016, INAC, 2010, Müllerová et al., 2011), drillings and mining (Adams and Lamoureux, 2005, Elberling et al., 2007, Kearns et al., 2015), seismic surveys (Dabros et al., 2018, Emers and Jorgenson, 1997, Felix and Raynolds, 1989a, Felix and Raynolds, 1989b, Howard et al., 2014, Kemper and Macdonald, 2009b, Walker et al., 2019) and off-road driving (Abele et al., 1984, Arp and Simmons, 2012) present major risks for vegetation damages in the Arctic from industrial activities. The intensity of the damage depends to a large degree on the weight and ground pressure of the impactor, which may be as light as a hiking person or as heavy as a seismic truck or tracked caterpillar. Equally important to the weight is the softness of the ground and the vegetation type. A heavy truck driving on a professionally built ice road in winter may result in no impacts to the vegetation, whereas driving in summer over a dry heath with the same vehicle may be devastating to vegetation, permafrost and landscape. The design of the tires or tracts of a vehicle influences the ground pressure of the impactor, which has a huge influence on the potential for disturbing the vegetation. Wide rubber tires especially made for driving on the tundra has a wide contact area between plants and vehicle, which reduces the ground pressure per area and therefore its impact and potential for vegetation damage. A table of disturbance examples and severity of impact is shown in Table 5. Several guidelines and regulations exist in Greenland to avoid or minimize environmental impacts, including vegetation damages. For any field activity (of any extent) related to mineral resources (excluding hydrocarbons) the rules for fieldwork and reporting (Link) apply. Depending on the magnitude and character of the activities a number of other guideline may apply or be relevant, e.g., Guidelines for preparing an Environmental Impact Assessment (EIA) report for mineral exploitation in Greenland (Link), Guidelines for Waste Handling from Temporary Work Camps (Link) or Onshore Seismic Surveys in Greenland (Link) for avoidance of major impacts, as well as guidelines for camp waste handling.

Table 5. Classification of disturbance by activities and their initial modification to vegetation, soils and sediment. Overview of causality of changes to the vegetation from various activities. 1-4 indicates increasing severity of the modification. Modified from Lawson (1986).

Severity of disturbance	Initial modification	Types of activities
1	Trampling and compaction of vegetation	a. off-road vehicle movements, single and multiple passes by wheeled and ski-mounted vehicles
		b. snowpads (e.g. winter trails)
		c. footpaths
		d. temporary storage facilities
2	Killing of original vegetation	a. hydrocarbon spills (diesel, crankcase oil, etc.)
		b. boardwalk and elevated buildings
		c. solid waste (e.g. steel drums, taps, woodpiles, non-degradable waste)
		d. berm (spoil piles) formed along bulldozed trails and excavations
3	Removal of vegetative mat	a. shallow bulldozed roads
		b. shallow excavations for building foundations
		c. piling (local)
		d. tracked vehicle movements
4	Removal of nearsurface sediment	a. bulldozed roads
	with vegetative mat	b. excavations of trenches, drainage ditches and sumps
		c. basement excavations for drill rig piling

4.1 Methods for assessing vegetation damage

Several methods exist to assess vegetation damages. Generally, damages are assessed by comparing two surfaces – the disturbed site against a similar, but undisturbed site in the same area. Ideally, the area was described and potentially photographed before the disturbing activity took place in order for the impacted area to serve as control for the damages. Normally, the degree of plant coverage, species composition and production is compared between the disturbed and undisturbed site (Møller and Strandberg, 1991). However, also structural changes could be assessed such as broken stems, damaged tussocks, soil compression and how visible the disturbance is. Assessment of production is cumbersome and normally only carried out where the area has importance for grazing wild stocks. The simplest method to compare the degree of difference / similarity in species composition between two sites is the similarity index, QS:

$$QS = \frac{2c}{a+b} * 100,$$

where: a = number of species in test site 1 (impact), b is number of species in test site 2 (control), and c is the number of shared species among the two sites. QS can vary between 0 and 100 (Mueller-Dombois and Ellenberg, 1974). However, a disturbance can also be defined as “any factor that brings about a significant change in the ecosystem leaf area index (LAI) for a period of more than one year” (Waring and Running, 2007). Along the lines of Mueller-Dombois and Ellenberg (1974), this change in LAI may then be compared between two sites (disturbed vs undisturbed) as exemplified above. More modern approaches use telemetry to measure the vegetative cover and greenness of an area as well as disturbances (Cohen and Goward, 2004, McDowell et al., 2015). For example, the normalized difference vegetation index (NDVI) is a normalized ratio of the near infrared (NIR) and red bands and is sensitive to the chlorophyll content of the vegetation. The NDVI changes over the growing season and can also be used to assess vegetation changes following disturbances. If the vegetation dies or is removed the NDVI changes instantly. Other options are to use the enhanced vegetation index (EVI) which is sensitive to changes in the vegetation's condition (Huete et al., 2002), or radiometric land surface temperature (LST) which is strongly related to vegetation density (Schmugge et al., 2002).

The essential point is to quantify the damages based on up-to-date pre-activity knowledge, to describe the impact of a given project and potentially to restore the affected area appropriately.

5 Re-establishment of vegetation

Following physical disturbances to an area, it is important to consider the best options for restoring the site to its former state by means of revegetation. This is especially important in the light of secondary effects from vegetation loss on permafrost, hydrology and erosion, as well as potential acceleration through climate change and the overall aesthetic impression of the area. Re-vegetation is defined as reestablishment of a coherent vegetative cover over disturbed lands. It was first defined by Bliss (1970) (referenced in Johnson and Cleve (1976)). In the literature there is a distinction between natural revegetation following naturally occurring disturbances such as bush fires, and revegetation following anthropogenic disturbances.

Natural revegetation is the process of succession of natural vegetation from the seed bank and rooting ability of plant remains in the disturbed area as well as from arriving seeds and bulbils from neighbouring plants in the area (Hagen 2002). Recovery succession culminates in a balance, as in the pre-disturbed condition, with no further changes in species composition, termed the climax community. As opposed to primary succession which is on recently exposed ground without any organic content, recovery succession benefits from the microorganisms, nutrients, living plant parts and seeds already present in the soil (see for example Těšitel et al. (2014) or Jones and Henry (2003) for recent examples of primary succession following retraction of a glacier). Due to the disturbance, there is often also a larger amount of nutrients in the ground. If neighbouring areas have continued plant growth and therefore seeds and plants (vegetative propagation) remain available for the revegetation.

There are a number of methods to aid the process and revegetate / restore a disturbed area to the pre-disturbed climax condition (is outside the scope of the report but see Møller and Strandberg. 1991). Assisted revegetation could be considered as natural revegetation is an extremely slow process in the Arctic (Forbes et al., 2001, Johnson and Cleve, 1976, Kearns et al., 2015). It may take hundreds of years before a disturbed area again reaches a climax community (Johnson and Cleve, 1976) due to the general restraints of plant growth in the Arctic (Chapter 2.4,

Table 1. Main restrictions for plant growth in the Arctic. Arctic species are adapted to the conditions listed in the table. (Based on Billings, 1987, Crawford, 1989, Giblin et al., 1991, Jonasson, 1997, Jonasson et al., 1999, Jonasson et al., 1996, Larcher, 1995, Semerdjieva et al., 2003, Shaver and Cutler, 1979, Ulrich and Gersper, 1978).

Low air and soil temperatures
Very short growing season
Encapsulation in snow or ice
Freezing
Limited availability of nutrients, due to slow decomposition
Drought
Nutrient buffer is in microbes during the growing season
Increased UV-B radiation
Permafrost and shallow active layer
Long-lasting snowdrifts
Flooding at thaw

To plan a revegetation process, it is important to understand the natural uncontrolled succession process of a corresponding area (Cargill and Chapin, 1987). This also aids in the evaluation and determination of the target condition of the restauration process, as well as on how to reach it. Sometimes it is for example desirable with fast intervention for erosion control before the target is aimed at the pre-disturbance condition. In Greenland, the vegetative communities often consist of climax societies and it can therefore be necessary to include knowledge from succession studies in vegetation that has not reached climax yet, from other but similar areas (Jones and Henry, 2003, Matthews and Whittaker, 1987, Těšitel et al., 2014). The road to the balanced climax society can follow different paths as described by Cargill and Chapin (1987) and will also depend on the environmental conditions such as nutrient availability, water and temperature of the area (Jones and Henry, 2003).

A number of reviews and peer-reviewed articles exist covering revegetation which should be consulted during an environmental impact assessment process as well as when damages occurs (Forbes et al., 2001, Jorgenson et al., 2010a, Jorgenson et al., 2015, Jorgenson et al., 2003, Kemper and Macdonald, 2009a, Kemper and Macdonald, 2009b, Kevan et al., 1995, Lamoureux et al., 2014, Lawson, 1986, Møller and Strandberg, 1991, Pearce et al., 2015, Streever et al., 2003, Vavrek et al., 1999, Walker et al., 1987, Walker, 1997).

We recommend the following reviews for an introduction to the field: Dabros et al., 2018, Forbes et al., 2001, Forbes and Jefferies, 1999, Møller and Strandberg, 1991. However, before a revegetation plan is made, it is imperative that the damages are assessed by botanists familiar with the Arctic flora as well as the Arctic physical processes, and that this expertise approves on the concept and plan for revegetation.

6 Protection of vegetation by regulation of anthropogenic activities

The exploration of the Arctic for oil and gas deposits took off in the late 1950ies in Arctic Canada and USA, and from this époque multiple examples exists showing how vegetation damages can occur, persist and alter permafrost and scar the landscape for decades. Therefore, a multitude of studies were carried out in the 1960-1980ies in order to develop methodologies and guidelines for reducing the footprint on the environment. These are the basis of the chapters above. The studies, however, let both Canada and Alaska to develop a suite of principles and regulation of so-called tundra activities in order to mitigate vegetation damages with potential secondary effects on permafrost, hydrology and erosion. This regulation is to day well established and will be covered in the following chapters.

6.1 Regulation in Alaska

There are many different types of activities related to extraction of oil / gas and minerals taking place in Alaska. The activities themselves, such as drilling or mining, damage the vegetation, and the required machinery is very specialized, most often very heavy and must be driven off-road across the tundra to get to the required location, which is also very damaging to the vegetation and permafrost if not mitigated. Therefore, strict regulation is enforced in State of Alaska, pertaining to this transportation with guidelines for where and when to drive on the tundra (activities in federal lands of Alaska is regulated in similar ways).

Note that the regulation of these activities in the federal lands of Alaska may deviate from the state-regulation, and that they are subject for approval by the Bureau of Land Management (see for example BLM 2020).

Winter tundra travel in Alaska

The dogma of the Alaskan guidelines can be described as 'Take only data, leave only footprints'. This should be applied by only moving about the Arctic tundra by driving over hard frozen snow-covered ground in winter on so called winter roads purposefully constructed of ice and compacted snow. When the ground thaws in spring the tundra closes completely for traffic. In summer driving is only allowed with tested and approved vehicles (State-of-Alaska, 2015). There are specific guidelines for when the ground is frozen hard enough to support construction of winter roads and for when the tundra can be opened for off-road driving (see examples from Canada, Alaska and Greenland in Table 6).

Driving is allowed in the relatively flat coastal area when there is an uncompressed snow cover depth of min. 6 inches (app. 15 cm) and the ground is frozen to at least -5 ^{o}C at a depth of 12 inches (app. 31 cm). In the hillier foothills area the snow depth must be at least 9 inches (app. 23 cm deep). The reason for the difference in snow depth between the two areas is due to differences in both macro and micro topography. In the foothills there is for example more tussock tundra vegetation that is more sensitive to disturbance and therefore requires a thicker snow cover to be adequately protected (Head et al., 2019). In the federal lands of Alaska, the snow depths shall be 9 inches

(23 cm) or 3 inches (7.5 cm) over the highest tussocks along the line of vehicle travel (BLM, 2020). These procedures ensure that the active layer is frozen hard and can carry the load of the heavy vehicles without leaving tracks in the ground, which means that both the vegetation and permafrost table is protected. Monitoring stations measuring ground temperature and snow cover have been established throughout state land on Alaska's North Slope, which means that data on snow depth, snow density, and soil temperature are collected autonomously and continuously throughout the early winter season (State-of-Alaska, 2018). Alaska Department of Natural Resources (ADNR) analyzes the data and decides when an area opens for traffic, which happens when the thresholds are met at *all* monitoring stations within an area (Head et al., 2019) (see http://dnr.alaska.gov/mlw/tundratravel/). This means that the period of the open season changes from year to year (Head et al., 2019). The industry must also monitor the snow depth and structure following a protocol developed by the ADNR (Head et al., 2019), and the data collected in the monitoring by ADNR is used to ground truth data form the industry. If the temperature rises and the snow becomes too soft during the open period, operations are halted until the temperature drops sufficiently to support the vehicles again. If these procedures are adhered to, only slight vegetation damages are observed, which takes few years to recover entirely (Melissa Head, pers. comm.). Besides from adhering to the general rules, individual routes of travel must be approved prior to driving with written authorization by ADNR. Such application must among others contain a map showing the location and anticipated schedule of operation, as well as a list of all vehicles/equipment intended used.

Table 6. Examples of present regulation of winter tundra activities in Alaska, and Yukon, Canada, compared to the regulation in Greenland in the 1980ies. For suggestions to present day mitigation of anthropogenic tundra activities in Greenland consult Kyhn et al. (2020).

Regulation	Alaska, Us	Yukon, Canada	Greenland, 1980ies
Ground frozen hard enough	-5 °C at 30 cm soil depth	When ground can support vehicle	When ground can support vehicle
Snow depth at plains (level)	6 inches/15 cm	10 cm	Sufficient snow
Snow depth at hills (slopes)	9 inches/23 cm	10 cm	-
Snow cover in sensitive vegetation	-	-	20 cm
Distance to pingos and eskers	-	150 m	-
Permitted in discontinuous permafrost	-	No	-
Who collects temperature and snow data	State	State	Operator
Crossing of water bodies		No	Yes
Buffer zone btw road and water body	No	30 m	No
Rehabilitation	Damaging party	Damaging party	Damaging party
Regulation of water use	Yes	Yes	Yes
Restrictions on vehicle type	Yes	Yes	Yes

At the center of the Alaskan regulation lies a decision by the ADNR to map the entire area of interest with respect to the vegetation's sensitivity to physical disturbances (Head et al., 2019) (Figure 11). This is a determining factor for the operators to choose the best possible route across the wilderness. All routes must be approved by the ADNR (in federal lands by Bureau of Land Management). This means that the open season can be extended by carefully choosing routes based on vegetation and landforms that are more resistant to damage, which also allows ice/compacted snow roads to be prepared in the pre-packing period with the use of low impact vehicles (Head, 2016).

Besides from regulation to protect the vegetation and permafrost, wide-ranging regulation exist to protect water-ways, river banks, fish-bearing waters, forest, wildlife, archaeological sites and cultural values among others (State-of-Alaska, 2013). Risk of oil spills are important to consider both in terms of vegetation damages and permafrost, but also with respect to water-ways and for example fish (State-of-Alaska, 2013). Further, a number of general mitigation measures are described to protect among others water ways, wildlife and cultural sites (State-of-Alaska, 2013). On top of this, the industry develops their own guides to *Best practices* according to the official guidelines to reduce their environmental footprint during operations (R. McManus Consulting Ltd. et al., 2004).

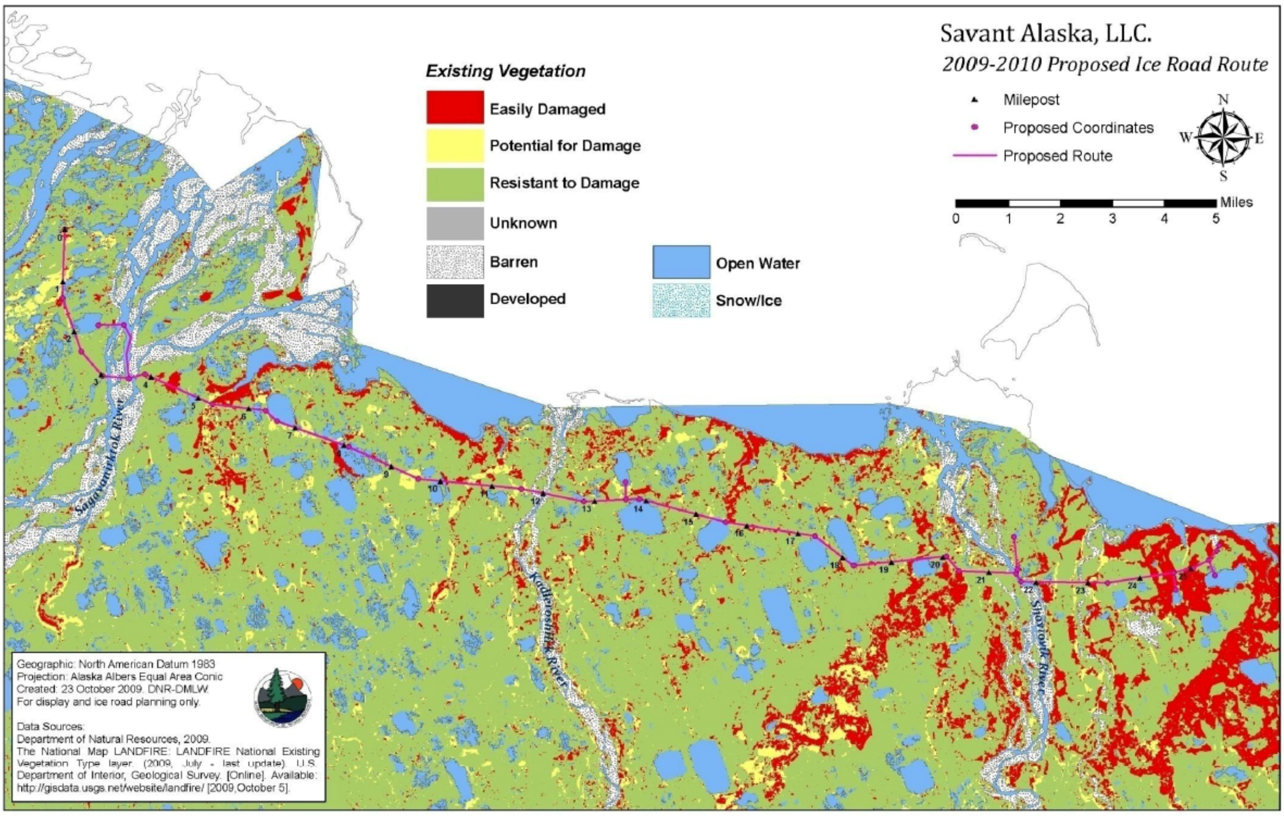


Figure 11. Vegetation sensitivity map of the North Slope of Alaska. The map is used as guidance when new travel routes are applied for. All travel routes must be authorized in writing by Alaska Department of Natural Resources before they can be used. From Head et al. (2019) and printed with permission from M. Head, Department of Natural Resources, State of Alaska.

Summer tundra travel in Alaska

The tundra is especially fragile when the snow is gone and there is no snow cover to protect the vegetation against the impact of vehicles. In spring, no traffic is allowed because the tundra is saturated from the snowmelt and therefore extra prone to damages. In the summer, when the tundra is dried up, traffic is allowed, but only under strict regulation. This period is from July 15^{th} until freeze-up. The core of this regulation for summer activities pertains to the weight per cm^2 of the vehicles in use. The lower the pressure per square centimeter, the lower the impact on the vegetation and permafrost. Vehicles that have a low ground pressure are termed low impact vehicles and typically have very wide low-pressure tires. An early example of such a vehicle is shown in Figure 12. Low impact vehicles however may also be rubber tracked. The central point is that all vehicles to be approved must be tested before hand according to a specific standard (see www.dnr.alaska.gov). The typical ground pressure of approved vehicles is below 2 PSI (= 0.138 bar or 13.8 kPA), but there is no requirement on maximum ground pressure level, instead each type of vehicle must pass the test. Low pressure vehicles approved for summer driving may be used in to build ice-roads in the prepacking period (Head et al., 2019).

Table 7 below outlines the regulation of summer activities, which applies to all permits issued for summer tundra vehicles, excluding ACV / hovercraft. Only tested and approved vehicles may be used (see example in Table 8).

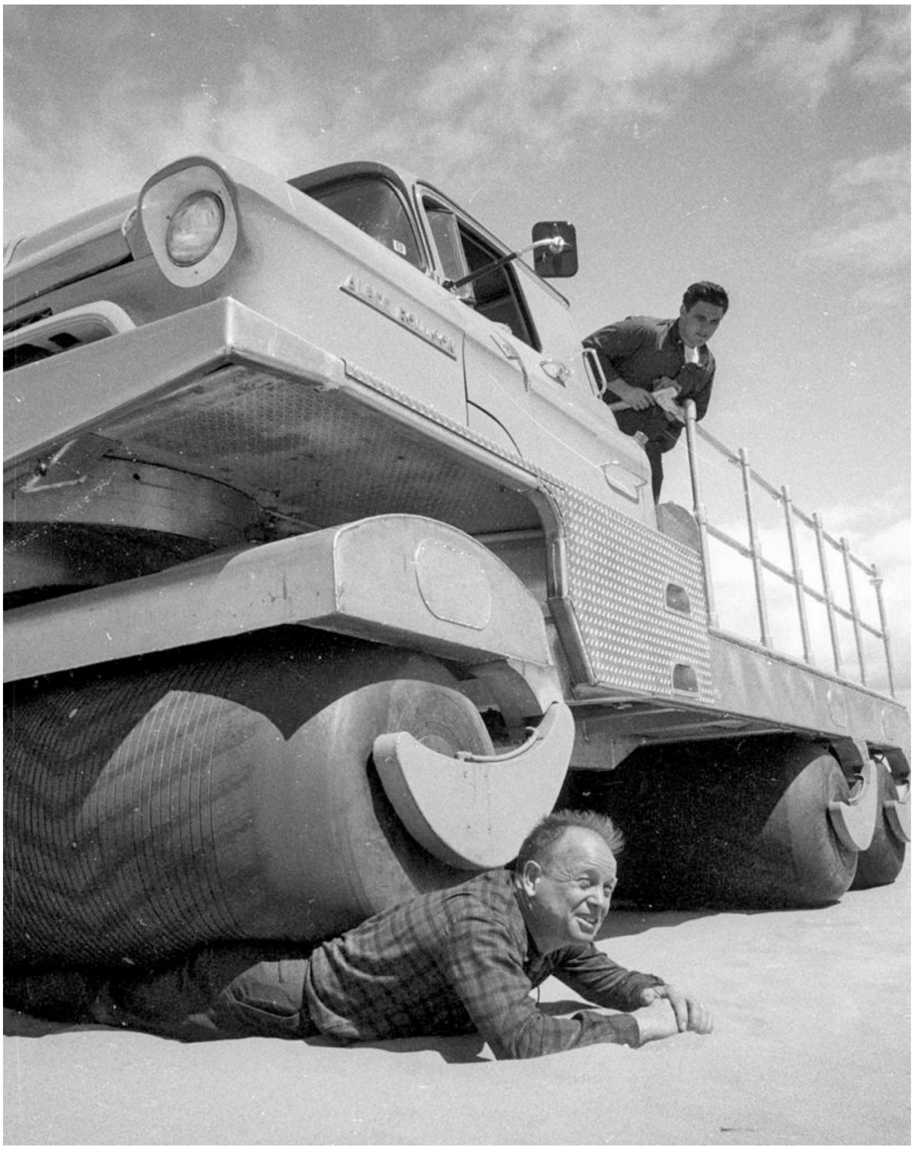
Table 7. Regulation of summer tundra activities, State of Alaska. DMLW = Division of Mining, Land and Water, Alaska.

1. Operations shall be restricted to dry uplands whenever possible.
2. The crossing of wetlands shall be kept to an absolute minimum.
3. The crossing of ponds, lakes, or the wetlands immediately bordering these areas is not authorized.
4. Minimum radius turns shall be avoided where possible.
5. Multiple passes over the same area shall be kept to a minimum.
6. All operators shall be made familiar with Arctic vegetation types to ensure compliance with the above.
7. The state reserves the right to limit, restrict, or require retesting of vehicles at any time.
8. Incidents of damage to the vegetative mat and follow-up corrective actions that have occurred shall be reported to the DMLW within 72 hours of occurrence. The DMLW will determine if additional rehabilitation actions are required of the permittee.
9. Vehicles cannot carry more payload than was carried during the certification test.

Table 8. Tested and approved vehicles for summer tundra activities 2017, Alaska, USA.

1. Argo 8 I/C with smooth tracks.
2. Argo 6X6 Frontier 580 with Supertracks.
3. Argo 8X8 Avenger 750 HDi with Supertracks.
4. Roller-driven vehicles equipped with large, bag-type tires (ex. Rimpull)
5. Haggland Bearcat with smooth track configuration.
6. Tucker Sno-cat with smooth track configuration.
7. Tucker-Terra Sno-Cat model 1600 with smooth track configuration.
8. Tucker Terra 2000 with smooth track configuration.
9. Pisten Bully 100 Trail with smooth track configuration.
10. Pisten Bully 400 Trail with smooth track configuration.
11. Polaris Ranger 800 6X6 configuration with smooth tires (maximum payload, including passengers, is 1,200 lbs).
12. Polaris Ranger 800 6X6 with smooth tires and plastic smooth-bottom sled (max payload is 2,100 lbs in vehicle and 1,000 lbs in sled).
13. Kubota RTV900 with Litefoot tracks (payload, including passengers, must be under 500 lbs).
14. Kubota RTV1100 with LiteFoot tracks (payload, including passenger, must be under 1595 lbs).
15. Lindsey Snow Walker (used only during pre-packing operations).
16. Airboats (for use in spill drills, exercises, and responses only).

Figure 12. Very illustrative example of an early 1950ies low impact vehicle, a so called rolligon with large low-pressure tires that reduces the weight per square centimeter on the ground. Rolligons have been used from the 1970ies onwards to travel off-road to oil fields in Alaska. Picture copied from [Historythings.]



As can be observed from Table 6, the regulation is strict and enforces protection of both vegetation and water-ways if adhered to. It is also apparent that damage to the vegetative mat is taken very seriously and must be reported immediately to the Alaska Department of Natural Resources Division of Mining, Land and Water. Further, a plan for restauration must also be submitted (State-of-Alaska, 2015) and the responsibility to carry through the rehabilitation lies upon the operator. Damages to the vegetation are thus not taken lightly upon, which relates to the potential for melting of the permafrost, erosion and subsidence.

Vehicles approved for summer activities may also be used in the fall to pack the snow and begin preparing winter roads. Here, the vehicles are adjusted to best possible protect the vegetation. Bulldozers are for example equipped with mushroom cups or smear blades that lifts the blades to avoid cutting the tops of hummocks, tussocks or high spots, which can lead to ground thaw and subsidence during spring. The same principles are followed during winter to best possible protect the vegetative mat.

6.2 Regulation in Canada

Canada is divided into thirteen provinces each with its own regulation. This chapter pertains to the regulation in the province of Yukon and the Northwest Territories (Northwest-Territories, 2015b, Yukon-Government, 2006).

Regulation in Yukon and Northwest Territories

The basis of the regulation in Canada is similar to Alaska, USA. The central dogma is to do as little damage as possible to the vegetation and permafrost achieved predominantly by restricting activities in the tundra and taiga to winter when the ground is frozen and snow covered. However, all-weather roads are permitted, but clearing and construction should be scheduled when the ground surface is strong enough to support equipment without rutting or erosion. The proponent should contact the local Indian and Northern Affairs (INAC) resource management officer prior to commencing construction to obtain permission. Construction should be suspended when conditions could result in serious erosion, such as heavy rainfall or when soils are saturated. To avoid rutting and erosion in permafrost terrain, overland travel is not permitted during summer months and road construction even of all-weather roads should only take place during late fall or winter when the active layer is well frozen (INAC, 2010). When planning all-weather roads special attention should be at preventing erosion and sedimentation for example at river crossings. The watershed delineation should be mapped completely for each stream to be crossed to determine the design requirements for a high flow, or so called '100-year flood events'. Not until expected peak flows are well understood stream crossing can be planned according to the guidelines stipulated in Table 9 (INAC, 2010). In permafrost terrain special care should be taken *not* to remove vegetation as the shade and insulation provided by the vegetation prevents ground thaw. Flowing water can further lead to rapid thawing and erosion of the ground, which means that running water should be channeled under all-weather roads through cross drains rather than cross ditches on the surface for all-weather roads.

Table 9. Stream crossings are vulnerable to erosion and sedimentation and requires special guidelines to protect water quality and fish habitat. From INAC (2010).

1. Minimize the number of stream crossings and use existing crossings where possible
2. Select or construct gently sloped approaches at right angles to the stream where the channel is straight, unobstructed and well defined, with a low bank height.
3. Locate stream crossings at sites with coarse-textured, well-drained material.
4. Locate stream crossings at least 500 m downstream of known fish habitat, such as spawning beds and rearing, feeding and overwintering site
5. Consider high-water marks in the design of stream crossings.

The required snow cover for driving off-road on the tundra in winter is only 10 cm and thus lower than in Alaska. However, there should be at least 10 cm of *compacted* snow on the road before heavier wheeled vehicles are permitted to operate. Further, there *is* a requirement for the ground being frozen hard enough to support the weight of the vehicles intended used, but it is not described to which depth it must be frozen in order to support their weight without damaging the vegetation and permafrost. However, since it is the responsibility of the operator to rehabilitate damage done to the vegetation or permafrost, there is incitement for being conservative and wait until the operator is certain that the ground can support ice-roads before they are built

(Northwest-Territories, 2015a). With regards to required snow cover there is no differentiation of requirements in specific areas, for example level vs sloped areas, and it thus appears a possibility that sloped areas are not as well protected as level areas. Once the tundra is open for driving all vehicles are allowed. It is recommended to utilize frozen lakes and rivers to reduce pressure on the vegetation (INAC, 2010). If an area has inadequate amount of snow it is allowed to haul in ice for preparing an ice-road. The Yukon guidelines are concrete in defining what must be protected (Yukon-Government, 2006). For example, the regulation does not approve driving near or on instable areas with a high near-surface ground ice content that may melt if the vegetation is damaged. That is for example polygon / patterned grounds, as well as fine-grained soils (particularly clays) and sedge wetlands and peatlands. It is further forbidden to drive within 150 m of pingos and eskers (INAC, 2010). Water ways are also strictly protected and except for stream crossings, water bodies should be avoided to prevent erosion and sediment deposition into the water. To prevent sedimentation and erosion, vegetated buffer strips of at least 30 m width are required to be left between roads and water bodies (INAC, 2010). Further, it is imperative to extend ice roads with snow fill-ups where rivers must be crossed, and several guidelines exist on how to build ice roads or river crossings safely (INAC, 2010). Nothing must be left behind, when the winter is over, which means that material for stabilizing 'snow bridges' must be removed (Northwest-Territories, 2015a).

6.3 Conclusion on regulation in the North American Arctic

The Alaskan and Canadian regulation build on bad experiences from the pioneering years in the 1950ies -1970ies where extensive damages to the tundra was observed (Babb and Bliss, 1974, Bliss and Wein, 1972, Lawson, 1986, Vavrek et al., 1999, Walker et al., 1987, Walker, 1997, Williams et al., 2013). There is however disagreements to whether these guidelines are sufficient to prevent damages from the heaviest vehicles, such as those used during terrestrial seismic surveys (Walker et al., 2019). These surveys cause up to 20 cm deep depressions or tracks on the tundra despite a snow cover that is thick enough according to the thresholds. These depressions change the microtopography within the track, which changes the snow distribution, hydrology and thermal regimes, which make the tracks visible from the air and in some areas causes thermokarst and erosion. It is therefore very important that the snow depth, deemed necessary before a given operation, is evaluated in the light of the specific activity, e.g. seismic surveys, as well as with respect to the vegetation and topography of the area in question. Therefore, a given area may require some years of collection of baseline data on snow density, distribution and depth as well as monitoring of ground temperature and thorough mapping of the vegetation in the area before it can be opened for operations in an environmentally safe matter.

7 Experiences from activities in Greenland

7.1 Background studies and environmental regulation related to vegetation in Greenland in the 1980ies

In the 1980ies seismic surveys were carried out in Jameson Land, East Greenland, and the foundation for assessing these surveys was based on the concepts of the North American Arctic as described above. Prior to the seismic surveys extensive geomorphological, biological and climatic background studies had been carried out (Anon., 1990).

There were two campaigns as described in detail in Kyhn et al. (2020); winter and summer with different strategies for protecting the vegetation. Environmental recommendations focused on minimizing effects on the vegetation, the active layer and the terrain. Beside of that there was focus on minimizing disturbance of the muskox and goose populations.

Geomorphological studies included among others soil temperatures and snow conditions. There is permafrost all over Jameson Land (Wallroth, 2010) and the studies showed that the active layer was up to 1.5-2 m thick (Nuna-Tek, 1989). Studies of the snow conditions (Thingvad and Søgaard, 1984) concluded, based on analyses of satellite images from 1975-80 and 1984 and field work in April 1984, that the snow cover was extensive in central Jameson Land, and a location 550 m a.s.l. had snow depths from 67 up to 110 cm. However, locally windblown ridges were snow free. Generally, and at all altitudes, field studies found snow depths between 60 and 100 cm with densities around 350 kg / m^3. At most sites the snow was wind packed with 'mean resistance' of 40 kg. The report concluded that these figures were comparable to North American localities.

The vegetation in Jameson Land was described in detail and vegetation types were mapped based on extensive field work (Bay and Holt, 1986). Bay and Holt described 4 surface types without vegetation (lakes, riverbeds, snow / ice, and bare ground / rock) and 14 vegetation types. The main vegetation categories were marsh, grassland, dwarf-shrub heath and snow beds.

Experiments were carried out using All Terrain Vehicles (ATV) and All Terrain Cycles (ATC) in the terrain in marsh, in lush dwarf-shrub heath, and areas with low cover of plants in August 1985 (Bay and Holt, 1985). Based on these experiments Bay and Holt concluded, that the effects of driving both with ATVs and ATC's in the relatively rare wet marshes would have unacceptable effects, while driving in the widespread heath types would have limited effects.

Based on the above, it was recommended to avoid driving in summer, and summer operations were therefore carried out using helicopter as means of transport of equipment. In addition to the summer activities, winter seismic surveys were carried out with regulations based on the above studies and experiences from North America.

7.2 Regulation of winter seismic activities, Jameson Land, Greenland, 1980ies

Seismic activities required an approval from the authorities. The approval was based on an impact assessment including the above mentioned studies as well as on experiences from North America. The approval of the winter seismic operations in 1987 (Anon., 1987) stipulated that surveys could be conducted during periods when the active layer had sufficient carrying capacity and protective snow or ice cover, that the vegetation or the active layer did not suffer mechanical injury.

The approval stipulated the following regarding vegetation and the active layer (MRA 1987):

- Seismic survey methods. Seismic surveys shall use the type of vibroseis trucks that were approved for use in the same terrain and used for the seismic surveys in 1985-86. For 1986, the general approval stated: The seismic program can be carried out using tracked vibroseis trucks,

- Survey periods and survey areas. Seismic surveys may only be carried out during periods when the active layer has such a carrying capacity and protective snow or ice cover, that the surveys can be carried out without vegetation or the active layer suffers mechanical injury,

- In especially robust areas, approved by the Greenland environmental authorities, seismic surveys may be carried out from 15. November until 1. January,

- In the period 15. November to 1. January, driving and placement of seismic lines may require approval by the Greenland environmental authorities. Prior to the approval, an official supervisor must have the opportunity to participate in the operator's reconnaissance of the area,

- Seismic surveys must be completed before the thawing of the active layer begins, or protection from snow or ice sheet thaws. After April 1, the supervisor can require that the survey work, including driving shall be terminated within three days, if the supervisor deems it necessary in order to protect the active layer and the vegetation,

- In areas with sensitive vegetation as specified in Appendix 2 (of the approval), driving as well as the location of seismic lines can be required approved by the Greenland environmental authorities. Prior to such approval, the supervisor must have the opportunity to participate in the operator's reconnaissance. For approval, it will be a condition that the area in question has an average snow depth of at least 20 cm, when the vibroseis studies are to be carried out.

It was up to the operator to determine that the provisions were met. However, periodic site inspections were made by the Greenland environmental authorities to reinforce the regulation.

The operator moreover compacted the snow on planned trails for heavy equipment (Vibroseis trucks, trailer camps) with a dozer or a 'Nodwell' at least 24 hours in advance. This allowed time to let the compacted snow freeze up.

7.3 Lessons learned – winter seismic surveys in Jameson Land in the 1980ies

The focus of the environmental regulation related to vegetation was to minimize the effects of driving on the wet vegetation types, which at the time were regarded as the most sensitive and was covering a relatively small proportion of the total land area. Further, these vegetation types were important for muskoxen and geese.

In 1989, study plots were established at vegetation damages at 15 locations in Jameson Land. Most of the study plots were located at sites where the inspection had found damages during the inspection in February 1986 and most of them were located in dry dwarf-shrub heaths. The study plots have been visited in 1995 and in 2020. None of these studies have been published yet, but a publication primarily based on the 2020 study is under way (Aastrup and Stewart, in prep).

Preliminary reports of the 1989-studies (unpublished) after the seismic surveys describe three main types of damages to the vegetation:

- Mixing of vegetation layer and upper layer of soil, was often caused by heavy equipment on an inadequate layer of snow when the belt 'circled round on the spot' or by light scraping of the upper layer by dozers. The damages, when inspected after a few years consisted of a mixture of dead plants and plant parts, living plants, and newly established plants,

- Scraping off vegetation leaving open bare mineral soil. These damages occurred when dozers scraped off too deep below the snow. Most of these damages were found on slopes and most had a limited extent as the dozer-drivers early in the season became aware of this type of damage,

- Frost damages. These damages consisted of frost-sensitive plants like Arctic bell heather (*Cassiope tetragona*) standing dead with intact branches. Frost damages were often found on relatively long stretches where the snow had lost its insulating properties because of the compaction caused by the heavy vehicles.

Most damages were regarded as limited without significant ecological effects (unpublished data). Tracks could be visible over several kilometers but scraping and mixing of the active layer and vegetation did not cover more than a few hundred meters. Except on a few sandy slopes, no instances of water- or wind erosion were observed.

In the long-term, it turned out, that damages were more pronounced in other vegetation types than the ones expected beforehand (wet vegetation types). Larger, contiguous damages were only observed in two types of 'dry dwarf-shrub heath' and in a 'snow bed' type. The type and degree of damage and visibility depended on the topography, soil conditions, and on the depth of the snow cover (Kyhn et al., 2020). No studies have been performed on impacts or changes to the permafrost and the active layer.

In August 2020, (Aastrup and Stewart, in prep.) found that damages or signs of damages were still found from both the movement of the trailer camp and from 'the seismic trains'. The tracks were visible from helicopter over much shorter distances than in 1995 (Figure 13). From ground it was difficult to discover and find the tracks except for a few sites (Figure 14). Even though it was difficult to find the tracks, preliminary analyses of the vegetation both in the tracks and in reference plots indicate, that vegetation had not returned to its initial state or had become identical to the surrounding vegetation.

The main preliminary conclusions of the field work in 2020 were:

- The visibility of the damaged vegetation had decreased except at the most damaged sites. It is no longer possible to follow the tracks on ground by vision except at a few sites. Tracks visible from helicopter can be very difficult to find and follow on ground,

- None of the tracks had returned to complete similarity with the reference plots. The similarity of tracks and references varied between about 65 and 75 % by species. Even at sites where the tracks were no longer clearly visible it was found that the species composition in the track and in the reference plots were not identical,

- There were more species in the tracks than in the reference plots,

- The frost damaged *Cassiope tetragona* heaths which are very extensive especially in the western part of Jameson Land, had not returned to the initial state. Instead, it seems that *Betula nana* has increased in occurrence,

- Climate change may play an important role in the vegetation development, which should be studied further,

- None of the previous marked damages showed signs of significant erosion, thermokarst or the like,

- No observations contradicted previous conclusions. No damages were found to be worse than observed during the field work in 1989,

- The small erosion spots found in 1989 were still only a few square meters in extension, but had not recovered in terms of plant cover.

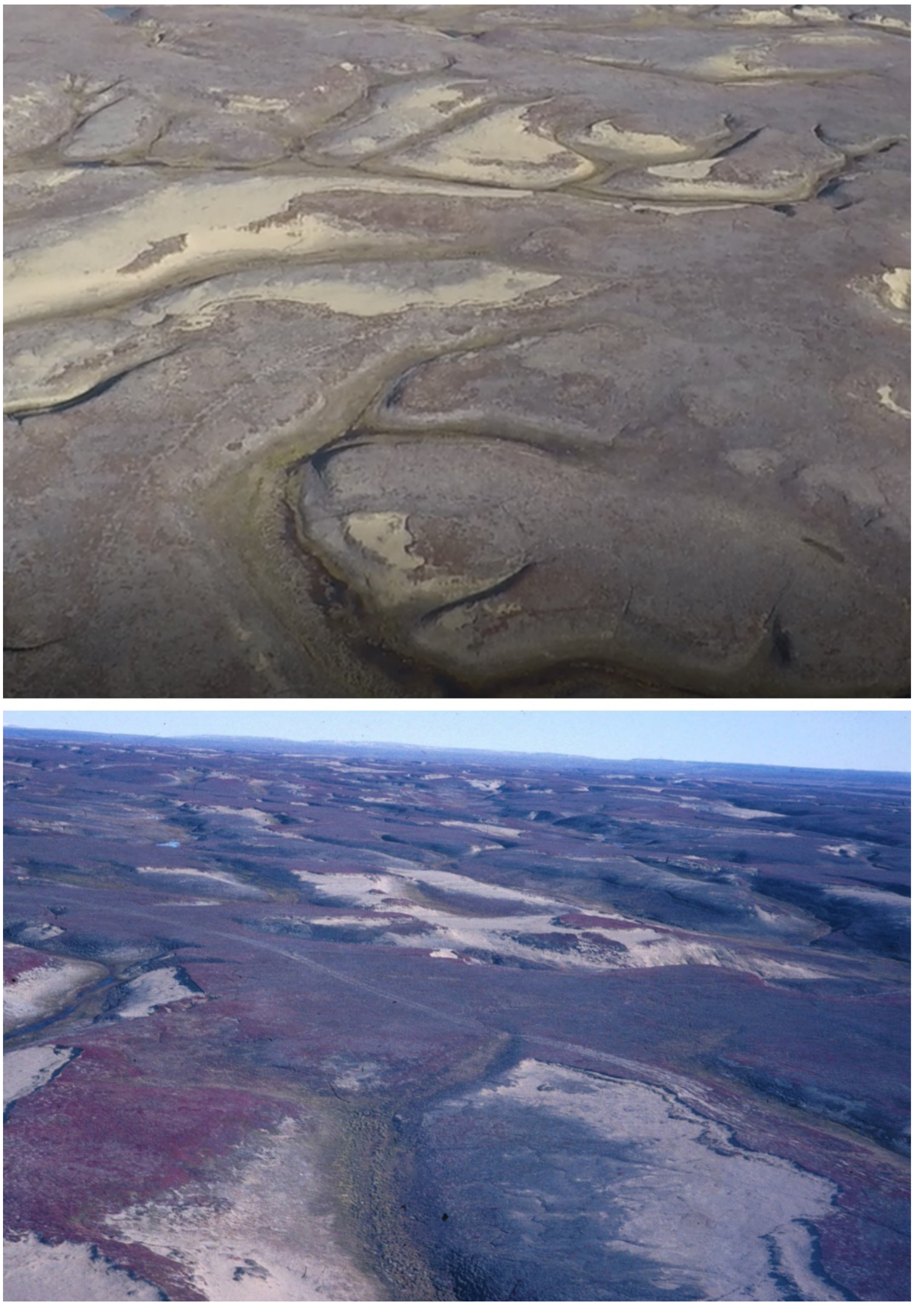


Figure 13. Tracks from the ARCO winter seismic operation in 1986 were still visible in Jameson Land here ten years later (upper photo, from 1996). Lower photo shows the same tracks in 2020 from the opposite direction. Tracks are still visible, although the tracks to the right in lower photo are difficult to see, as they also were from the ground. Photos: Peter Aastrup.

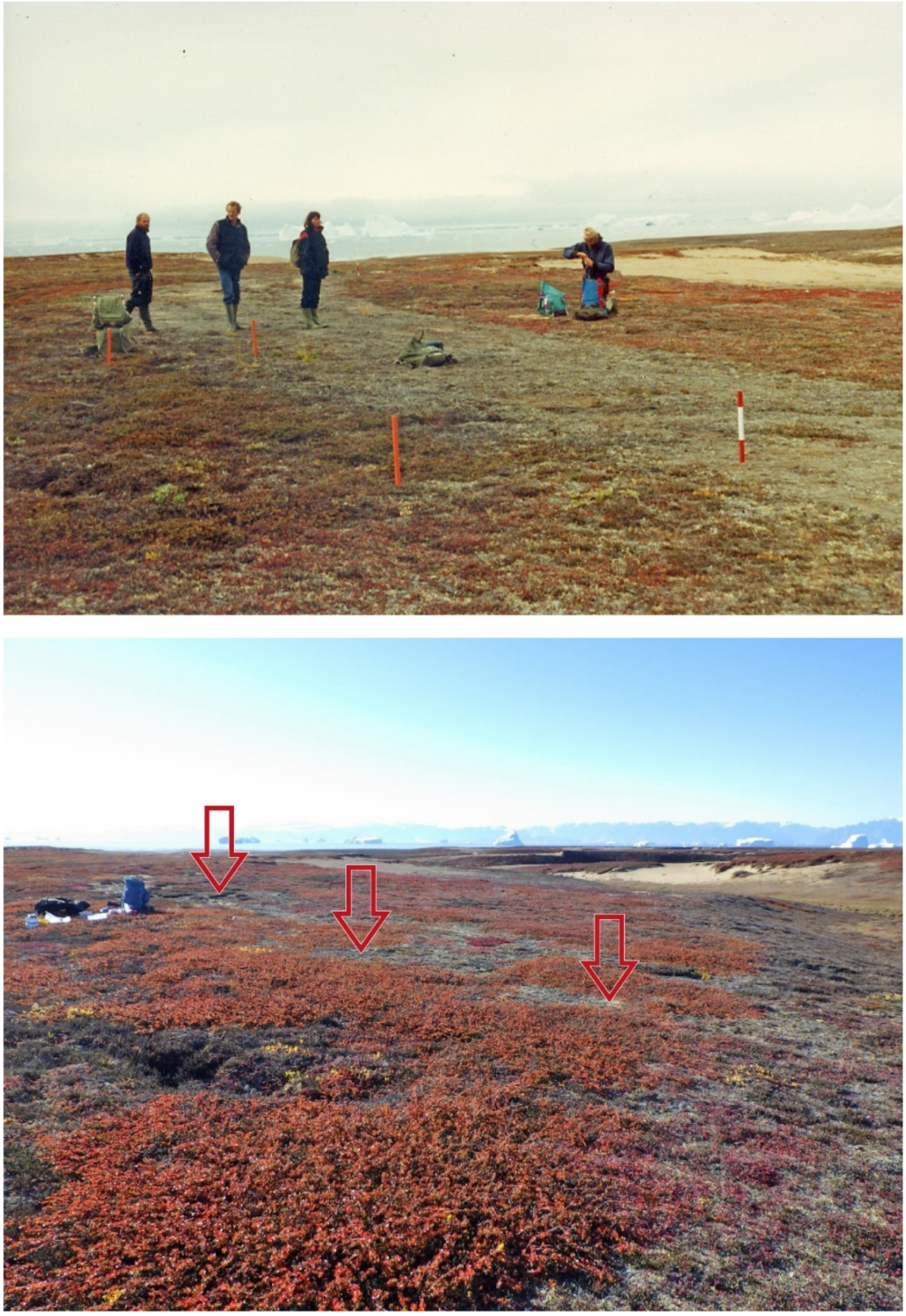


Figure 14. Same track as Figure 13 seen from the ground. Upper in 1989 and lower in 2020. Tracks are still visible indicated by red arrows along the left border on lower photo. Cassiope has not recovered, while Betula is covering a larger area than in 1989.

7.4 Conclusion on the 1980ies regulation of seismic activities in Greenland

Winter seismic operations

All in all, time has shown that no serious long-term effects of the winter seismic surveys have been found in terms of vegetation cover or erosion. In that sense, the recommendations and regulation were a success. It is important to be aware, however, that some of the main concerns about the wet terrain and vegetation types did not turn out to be problematic while the dry heaths with frost sensitive species like *Cassiope tetragona* turned out to be the most visible in the long-term, which was not anticipated or taken into account in the recommendations and regulation.

What then, was the basis for the success, and how could the long-term effects on the *Cassiope*-heath have been avoided? First, there is no doubt that the provisions about frozen-up ground and an adequate snow depth are the main reasons for the success regarding most vegetation types. The relatively few sites where there are still significant effects from the winter seismic surveys are in areas with inadequate snow cover, or where there was a lot of scraping-off-snow and dozers turning around. Further, sites at steep slopes that were difficult to pass are still visible. These sites demonstrate, that without specified provisions there could have been extensive tracks in the vegetation, and possibly effects on the active layer. We believe that the effects on the *Cassiope*-heaths come from frost as a result of compacted snow with decreased insulating properties compared to undisturbed snow, and / or from removal of snow causing frost damages in combination with increasing evaporation causing the plants to dry out. Regardless, the key for avoiding the damages would be a thicker protecting layer of un-compacted snow, especially above the *Cassiope*-heaths. Experimental studies on this issue would be highly appropriate as a basis for developing protection measures for this kind of heaths. Also, it should be noted that vegetation maps would help in developing graduated protection measures, if needed.

The seismic campaigns conducted in the 1980ies Jameson Land benefitted hugely from the experiences from the 1950ies onwards in the North American Arctic. The required environmental recommendations and approval of placement of the seismic lines and snow roads for moving the trailer camps probably also contributed to the long-term relatively small effects on the vegetation. However, it became apparent during the winter campaigns and the studies conducted at the time, that to protect the vegetation sufficiently, the snow depth had to be deeper than 20 cm, which from the onset was only required over sensitive vegetation (Anon., 1987). There was a large degree of site inspections and high level of communication between the operator and the Greenland environmental authorities which contributed to the low level of serious impacts on the vegetation and terrain

Summer seismic operations

Following the winter activities, 2D helicopter-seismic surveys were conducted in summer under a new set of regulations (Anon., 1989), built on definitions of sensitive periods and sensitive areas where the authorities had to approve seismic activities and no-go areas for specific periods. All equipment was transported by helicopter and explosives were used as sound source and detonated in shot holes. Therefore, the use of heavy vehicles was minimized in relation to winter seismic surveys, which likely contributed to the low observed impact on the vegetation. Further, the approval of the seismic summer activities prescribed mitigation of damages to terrain and vegetation around the seismic shot holes.

The work could commence from June 15 when the worst snow melt was over. In areas with sensitive vegetation, seismic lines needed on-site approval by the authorities. In the period August 1 to October 1, all seismic lines and shot hole points had to be approved by the Greenland environmental authorities in areas with sensitive vegetation. Areas for infrastructure should as far as possible be selected so that the vegetation would be damaged as little as possible. Shot lines had to be selected to be not closer than 30 m from streams, ponds and lakes. Shot lines should be selected ‘outside’ important sites like archaeological remains, pingos, triangulation points and other sites of historical interest. Around shot-holes the terrain damages had to be restored and the vegetation put back. A number of studies were conducted to examine the effects on the vegetation, and the impact was very small. Potential impacts on the extent of the active permafrost table were not studied.

8 Recommendations for best practices to avoid vegetation damages from driving with heavy equipment in Greenland

Based on the studies, experiences and regulations in the North American Arctic and in Greenland, recommendations for best practices to avoid and minimize vegetation damages from driving with heavy vehicles can be formulated. These recommendations are relevant for all activities requiring off-road driving in the Arctic environments in Greenland and can be included in the regulation of the activities.

For future campaigns in Greenland, the areas of interest should be monitored beforehand in terms of temporal and spatial snow distribution, and the vegetation should be mapped in terms of sensitivity to physical disturbances. Like in the North American Arctic focus should also be directed at potential negative impacts on permafrost, hydrology, sedimentation and erosion, and it would be advantageous to map the extent of permafrost and depth of the active layer in the area of interest before extensive field work is conducted. Mapping of all rivers, streams, ponds, fens and wetlands would be very advantageous for placing future roads or for example seismic lines. Below are listed recommendations for future exploration activities of tundra areas in Greenland. See also the recommendations to the contents of an environmental impact assessment of onshore seismic surveys in Greenland (Kyhn et al. 2020).

8.1 In general

Following general best practices are recommended:

- Use only vehicles meeting BEP and BAT principles,
- Follow best practices for mitigation of effects from seismic surveys according to Kyhn et al. (2020),
- Establish efficient communication between authorities and operators to prevent misunderstandings regarding when and where for the operations,
- Prepare plans for best possible rehabilitation should damages occur (Møller and Strandberg, 1991). Decide what the goals for rehabilitation of the vegetation is. Establish the necessary steps and threshold for success,
- Damage to the vegetative mat and follow-up corrective actions shall be reported to the authorities (EAMRA) as fast as possible. The authorities will determine if additional actions are required of the operator,
- Planned routes shall take into account:
    - Sensitive vegetation, which shall be avoided,
    - Pingos, other sensitive geomorphological features and historical sites shall be avoided with minimum 150 m,
    - Water bodies and steep slopes, which shall be avoided as far as possible and approval is necessary if it is needed to cross such areas.

8.2 Winter

Experiences from Jameson Land winter seismic surveys indicate that:

- Snow cover is important. The deeper the snow, the less impact on the vegetation,
- Freeze up of soil is important. The more frozen the soil is, the less impact,
- Damages was dependent of vegetation types. Vegetation types with frost sensitive species like Arctic bell heather (*Cassiope tetragona*) suffered from compaction of snow which reduced its insulating properties, while vegetation types with for example bog bilberry (*Vaccinium uliginosum*) or Arctic willow were less sensitive. According to experiences from Alaska, preparation of snow roads diminishes damages for most vegetation types. It is important, however, to be aware, that frost sensitive species may not benefit from preparation of snow roads. In Greenland there are no experimental studies on the effects of snow preparation, and experiences from Low Arctic Alaska are probably not relevant for high Arctic Greenland,
- Vegetation maps helped planning surveys to minimize effects on the most sensitive and ecologically important vegetation types,
- Line scouting was critical to for the movement of the trailer camp with respect to topography and vegetation,
- Timing of seismic surveys is important in relation to snow cover and frozen ground,
- Mechanical disturbances can be clearly visible, although the spatial extent of such damages were small thanks to vehicle drivers following the guidelines,
- Experiences from Jameson Land indicate that Alaskan regulations may not be adequate / sufficient for all vegetation types in high Arctic Greenland.

The key factors to avoid or minimize vegetation damages are the depth of the snow layer and freeze up of the ground and soil beneath the snow. Differential regulation measures, taking various vegetation types into account, requires vegetation maps.

Important background knowledge that should be available before an application for winter seismics or other activities with heavy vehicles can be evaluated include knowledge of:

- The distribution of permafrost and active layer extension in time and space.
- Vegetation types and their sensitivity to anthropogenic activities – in time and space.
- The area of interest in terms of rivers, streams, ponds, fens and wetlands, as well as topography to appoint potential appropriate crossings and to avoid water contamination.

Following are generally recommended (adapted from Alaska regulation, Table 6):

Activities shall await:

- Until the ground is frozen, (in Alaska the temperature shall be -5 °C at 30 cm soil depth),
- Snow depth is at least 25 cm in all terrains.

However, in areas where winter conditions are less severe than in the north and where permafrost is absent or less developed a specific evaluation of snow and ground may be actual before activities can be initiated.

8.3 Summer

No long-term studies of the effects of summer seismics or activities with heavy vehicles in Greenland are available. However, the Jameson Land experience showed that the helicopter seismic campaign impacted little on the vegetation.

But, based on the experience from Canada and Alaska, DCE and Greenland Institute of Natural Resources (GINR) recommend that seismic surveys in Greenland are carried out in winter, when the terrain is frozen and snow-covered. Summer operations (with driving equipment) should be restricted to areas where a winter operation is impossible to do, and to areas of a limited extend, where for example all driving and transport can occur in less sensitive habitats such as dry gravel plains and river beds.

In case of summer activities including seismic operations the following is recommended:

Important background knowledge that should be available before an application for summer off road driving with heavy vehicles including seismic activities can be evaluated include knowledge on:

- The distribution of permafrost and active layer extension in time and space,
- Vegetation types and their sensitivity to anthropogenic activities – in time and space,
- The area of interest in terms of rivers, streams, ponds, fens and wetlands, as well as topography to appoint potential appropriate crossings and to avoid water contamination,
- Whereabouts of pingos, thermokarsts, sensitive areas and historical sites etc.,
- Which low-pressure vehicles that can be used (BAT).

Following rules are recommended to be applied in the field (adapted from Table 7):

- Operations shall be restricted to dry uplands whenever possible,
- The crossing of wetlands shall be kept to an absolute minimum. However, riverbeds with gravel can be crossed and also used as transport corridors,
- Minimum radius turns shall be avoided where possible,
- Multiple passes over the same area shall be kept to a minimum,
- The operator shall be made familiar with Arctic vegetation types to ensure compliance with the above.

8.4 Recommended baseline studies in relation to onshore seismic operations in Greenland

In areas where driving with heavy vehicles, including seismic surveys, are planned, the vegetation types should be mapped (aided by satellite images combined with ground-truthing studies) and knowledge on snow depths and freezing time of the active layer throughout the survey area should be recorded prior to onset of seismic or operations with heavy vehicles.

The experience from the Jameson campaign in the 1980ies also revealed a lack of knowledge on the effects of High Arctic vegetation types to driving and preparation of snow roads. Studies to elucidate effects of driving in these vegetation types both summer and winter and especially under different snow regimes including compaction of snow (snow roads) are needed to regulate future activities.

9 References

Abele, G., J. Brown and M.C. Brewer 1984. Long-term effects of off-road vehicle traffic on tundra terrain. *Journal of Terramechanics* 21: 283-294.

ACI-Assessment 2005. Arctic climate impact assessment (ASIA): Scientific report. Cambridge University Press, Cambridge.

Adams, P.W. and S. Lamoureux 2005. A literature review of the use of native northern plants for the revegetation of Arctic mine tailings and mine waste.

Anon. 1987. Godkendelse af A / S ARCO GREENLAND's planer om seismiske vinterundersøgelser Jameson Land 1987 - 88 (in danish). *Råstofforvaltningen for Grønland*: 41 pp.

Anon. 1989. Godkendelse af A / S ARCO GREENLAND's planer om seismiske sommerundersøgelser. Jameson Land 1989. *Raastofforvaltningen for Grønland*: 32 pp.

Anon. 1990. List of reports on background studies etc. in Jameson Land in connection with exploration and possibly production activitites in the region. Ministry og Energy, Mineral Resources Administration for Greenland. 7 pp.

Arp, C.D. and T. Simmons 2012. Analyzing the Impacts of Off-Road Vehicle (ORV) Trails on Watershed Processes in Wrangell-St. Elias National Park and Preserve, Alaska. *Environmental Management*. 49:751-766.

Auerbach, N.A., M.D. Walker and D.A. Walker 1997. Effects of roadside disturbance on substrate and vegetation properties in Arctic tundra. *Ecol. Appl.* 7: 218-235.

Babb, T.A. and L.C. Bliss 1974. Effects of Physical Disturbance on Arctic Vegetation in the Queen Elizabeth Islands. *Journal of Applied Ecology* 11: 549-562.

Bader, H.R. and J. Guimond 2004. Tundra Travel Modeling Project. Alaska Department of Natural Resources, Division of Mining, Land and Water, Alaska. 70.

Bay, C. 1992. A Phytogeographical Study of the Vascular Plants of Northern Greenland - North of 74° Northern Latitude. *Meddelelser Om Grønland* 36: 1-102.

Bay, C. 1997. Effects of experimental spills of crude and diesel oil on Arctic vegetation. A long-term study on high arctic terrestrial plant communities in Jameson Land, central East Greenland. NERI Technical Report. Vol. 205. National Environmental Research Institute, Roskilde. 44.

Bay, C. and S. Holt 1985. Undersøglse af nogle terrængående køretøjers indvirkning på vegetation og jordbund i Jameson Land, 1982-85 (in Danish).60 pp.

Bay, C. and S. Holt 1986. Vegetationskortlægning af Jameson Land 1982-86 (in danish). *Greenland Fisheries and Environmental Research Institute, Copenhagen.*: 40 pp.

Bennike O. 2009. Colonisation of Greenland by plants and animals after the last ice age: a review. *Polar Record* 35: 323-336.

Berendse, F. and S. Jonasson 1992. Nutrient Use and Nutrient Cycling in Northern Ecosystems. Academic Press, San Diego, California.

Bilings, W.D. and H.A. Mooney 1968. The ecology of Arctic and Alpine plants. *Biological Reviews*. 43: 481-529.

Billings, W.D 1987. Constraints to Plant Growth, Reproduction, and Establishment in Arctic Environments. *Arctic and Alpine Research* 19: 357-365.

Billings, W.D 1992. Phytogeographic and evolutionary potential of the Arctic Flora and vegetation in a changing climate. *In* Arctic ecosystems in a changing climate: an ecophysiological perspective,. I. Chapin, F.S., R.L. Jefferies, J.F. Reynolds, G.R. Shaver and J. Svoboda, editors. Academic Press, San Diego. 91-109.

Björn, L.O., T. Callaghan, Y. Chernov, T. Chapin, T.R. Christensen, B. Huntley, R. Ims, D. Jolly, S. Jonasson, N. Matveyeva, N. Panikov, W. Oechel and G. Shaver 2004. Ch06 - Arctic Tundra and Polar Desert Ecosystems. *In* ACIA Scientific Report. T.V. Callaghan, editor.

Bliss, L.C. and R.W. Wein 1972. Plant community responses to disturbances in the western Canadian Arctic. *Canadian Journal of Botany*. 50: 1097-1109.

Bliss, L.D 1970. Oil and the ecology of the Arctic. *Transactions of the Royal Society of Canada, Series IV*. VIII: 361-372

BLM 2020. Coastal Plain Oil and Gas Leasing Program. Record of Decision, Appendix A. US Department of the Interior Bureau of Land Management. Link

Boertmann, D.and C. Bay 2018. Grønlands Rødliste 2018. Fortegnelse over grønlandske dyr og planters trusselstatus. Aarhus Universitet, Nationalt Center for Energi og Miljø (DCE) og Grønlands Naturinstitut. https://natur.gl/guidance/the-red-list/?lang=en

Brooker, R. and R. van der Wal 2003. Can soil temperature direct the composition of high arctic plant communities? *Journal of Vegetation Science* 14: 535-542.

Brown, R.J.E. 1970. Permafrost in Canada. Its Influence on Northern Development. University of Toronto Press, Toronto.

Campbell, D. and J. Bergeron 2012. Natural Revegetation of Winter Roads on Peatlands in the Hudson Bay Lowland, Canada. *Arctic, Antarctic, and Alpine Research*. 44: 155-163.

Cargill, S.M. and F.S. Chapin 1987. Application of Successional Theory to Tundra Restoration: A Review. *Arctic and Alpine Research* 19: 366-372.

Chapin, F.S. 1983. Direct and indirect effects of temperature on arctic plants. *Polar Biology* 2: 47-52.

Chapin, F.S. and G.R. Shaver 1981. Changes in Soil Properties and Vegetation Following Disturbance of Alaskan Arctic Tundra. *Journal of Applied Ecology* 18: 605-617.

Claridge, F.B. and A.M. Mirza 1981. Erosion Control along Transportation Routes in Northern Climates. *Arctic*. 34: 147-157.

Cohen, W.B. and S.N. Goward 2004. Landsat's Role in Ecological Applications of Remote Sensing. *BioScience*. 54: 535-545.

Collins, C.M., C.H. Racine and M.E. Walsh 1994. The Physical, Chemical, and Biological Effects of Crude Oil Spills after 15 Years on a Black Spruce Forest, Interior Alaska. *Arctic*. 47: 164-175.

Cooper, E.J., S. Dullinger and P. Semenchuk 2011. Late snowmelt delays plant development and results in lower reproductive success in the High Arctic. *Plant Science* 180: 157-167.

Council, N.R. 2003. Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope. National Academies Press, Washington D.C. USA.

Crawford, R.M.M. 1989. Studies of plant survival: Ecological case histories of plant adaptation to adversity. Blackwell Scientific, Oxford.

Crawford, R.M.M., H.M. Chapman and H. Hodge 1994. Anoxia Tolerance in High Arctic Vegetation. *Arctic and Alpine Research* 26: 308-312.

Dabros, A., M. Pyper and G. Castilla 2018. Seismic lines in the boreal and arctic ecosystems of North America: environmental impacts, challenges, and opportunities. *Environmental Reviews* 26: 214-229.

Daniëls, F.J.A., L.J. Gillespie and M. Poulin 2013. Plants. *In* CAFF 2013. Arctic Biodiversity Assessment. Status and trends in Arctic biodiversity. Vol. 1. H. Meltofte, editor. Narayana Press, Denmark.

Elberling, B., H.H. Christiansen and B.U. Hansen 2010. High nitrous oxide production from thawing permafrost. *Nature Geoscience*. 3: 332.

Elberling, B., J. Søndergaard, L.A. Jensen, L.B. Schmidt, B.U. Hansen, G. Asmund, T. Balić-Zunić, J. Hollesen, S. Hanson, P.-E. Jansson and T. Friborg 2007. Arctic Vegetation Damage by Winter-Generated Coal Mining Pollution Released upon Thawing. *Environmental Science & Technology*. 41: 2407-2413.

Emers, M. and J.C. Jorgenson 1997. Effects of winter seismic exploration on tundra vegetation and the soil thermal regime in the Arctic National Wildlife Refuge, Alaska. *Disturbance and Recovery in Arctic Lands*: 443-454.

Farmer, A.M. 1993. The effects of dust on vegetation—a review. *Environ. Pollut*. 79: 63-75.

Feilberg, J. 1984. A Phytogeographical Study of South Greenland Vascular Plants. *Meddelelser Om Grønland* 15: 1-70.

Felix, N.A. and M.K. Raynolds 1989a. The Effects of Winter Seismic Trails on Tundra Vegetation in Northeastern Alaska, U.S.A. *Arctic and Alpine Research* 21: 188-202.

Felix, N.A. and M.K. Raynolds 1989b. The Role of Snow Cover in Limiting Surface Disturbance Caused by Winter Seismic Exploration. *Arctic*. 42: 62-68.

Forbes, B.C. 1998. Cumulative impact of vehicle traffic on high arctic tundra: Soil temperature, plant biomass, species richness and mineral nutrition. *In* The 7th International Permafrost Conference. Collection Nordicana, Yellow Knife.

Forbes, B.C., J.J. Ebersole and B. Strandberg 2001. Anthropogenic Disturbance and Patch Dynamics in Circumpolar Arctic Ecosystems. *Conservation Biology* 15: 954-969.

Forbes, B.C. and R.L. Jefferies 1999. Revegetation of disturbed arctic sites: constraints and applications. *Biological Conservation*. 88: 15-24.

Fredskild, B. 1995. A Phytogeographical Study of the Vascular Plants of West Greenland. *Meddelelser Om Grønland* 45: 1-157.

Giblin, A.E., K.J. Nadelhoffer, G.R. Shaver, J.A. Laundre and A.J. McKerrow 1991. Biogeochemical diversity along a riverside toposequence in Arctic Alaska. *Ecological Monographs*. 61: 415-435.

Gill, H.K., T.C. Lantz, B. O'Neill and S.V. Kokelj 2014. Cumulative Impacts and Feedbacks of a Gravel Road on Shrub Tundra Ecosystems in the Peel Plateau, Northwest Territories, Canada. *Arctic, Antarctic and Alpine Research*. 46: 947-961.

Gold, W.G. and L.C. Bliss 1995. Water limitations and plant community development in a polar desert. *Ecology*. 76: 1558-1568.

Goudie, A.S. 2004. Encyclopedia of Geomorphology. *In* Encyclopedia of Geomorphology. Vol. 1. A.S. Goudie, editor. Routledge, New York. 777 pp.

Hagen, D. 2002. Propagation of native Arctic and alpine species with a restoration potential. *Polar Research* 21: 37-47.

Halliday, G. and R. W. M. Corner 2019. A Flora of the East Greenland Central Fjord Region, 70°N-77°N. Trollius Publications.

Hansen, J., G. Asmund, P. Aastrup, A. Mosbech, C. Bay, M. Tamstorf and D. Boertmann 2012. Jameson Land. A strategic environmental impact assessment of hydrocarbon and mining activities. Scientific Report from DCE - Danish Centre for Environment and Energy. Vol. 41. Aarhus University.

Harris, S.A. 1986. Permafrost distribution, zonation and stability along the Eastern ranges of the Cordillera of North America. *Arctic*. 39: 29-38.

Head, M. 2016. Off-road travel management on Alaska's North slope. D.o.M. Alaskas department of Natural Resources, Land and Water.

Head, M., B. Baird and K. Maher 2019. State of Alaska Off-Road & Ice Road Management Practices. A.D.o.N. Resources. Division of Mining, Land and Water, Alaska.

Hollesen, J., B. Elberling and P.E. Jansson 2011. Future active layer dynamics and carbon dioxide production from thawing permafrost layers in Northeast Greenland. *Global Change Biology* 17: 911-926.

Holt, S. 1987. The Effects of Crude and Diesel Oil Spills on Plant Communities at Mesters Vig, Northeast Greenland. *Arctic and Alpine Research* 19: 490-497.

Howard, R.J., C.J. Wells, T.C. Michot and D.J. Johnson 2014. Effects of Disturbance Associated With Seismic Exploration for Oil and Gas Reserves in Coastal Marshes. *Environmental Management*. 54: 30-50.

Haag, R.W. and L.C. Bliss 1974. Energy Budget Changes Following Surface Disturbance to Upland Tundra. *Journal of Applied Ecology* 11: 355-374.

Huete, A. R., Didan, K., Miura, T., Rodriguez, E. P., Gao, X., & L.G. Ferreira (2002). Overview of the radiometric and biophysicalperformance of the MODIS vegetation indices. *Remote Sensing of Environment* 83: 195-213

INAC 2010. Northern land use guidelines. Access - roads and trails. Vol. 05. Indian and Northern Affairs, Gatineau - Quebec 39.

lves, J.D. and R.G. Barry 1974. Arctic and Alpine Environments. Methuen.

Jenkins, T.F., L.A. Johnson, C.M. Collins and T.T. McFadden 1978. The Physical, Chemical and Biological Effects of Crude Oil Spills on Black Spruce Forest, Interior Alaska. *Arctic*. 31: 305-323.

Johnson, L.A. 1980. The fate and effect of crude oil spilled on subarctic permafrost terrain in interior Alaska. Alaskan Projects Office, Cold Regions Research and Engineering Laboratory (U.S.). Alaskan Projects Office, Corvallis Environmental Research Laboratory.

Johnson, L.A. and K.V. Cleve 1976. Revegetation in arctic and subarctic North America. A literature review. Cold regions research and engineering laboratory, US Army. Directive of civil works and directive of military construction office, Chief of engineers, Hanover, New Hampshire.

Jonasson, S. 1997. Buffering of Arctic Plant Responses in a Changing Climate. *In* Global Change and Arctic Terrestrial Ecosystems. W.C. Oechel, T.V. Callaghan, T.G. Gilmanov, J.I. Holten, B. Maxwell, U. Molau and B. Sveinbjörnsson, editors. Springer New York, New York, NY. 365-380.

Jonasson, S., F.S.I. Chapin and G.R. Shaver 2001. Biogeochemistry in the Arctic: Patterns processes and controls. *In* Biogeochemistry in the Arctic: Patterns, Processes, and Controls. E.-D. Schulze, S.P. Harrison, M. Heimann, E.A. Holland, J.J. Lloyd, I.C. Prentice and D. Schimel, editors. Academic Press, New York. 139-150.

Jonasson, S., A. Michelsen, I.K. Schmidt and E.V. Nielsen 1999. Responses in microbes and plants to changed temperature, nutrient and light regimes in the Arctic. *Ecology*. 80: 1828-1843.

Jonasson, S., A. Michelsen, I.K. Schmidt, E.V. Nielsen and T.V. Callaghan 1996. Microbial biomass C, N and P in two arctic soils and responses to addition of NPK fertilizer and sugar: implications for plant nutrient uptake. *Oecologia* 106: 507-515.

Jones, G.A. and G.H.R. Henry 2003. Primary plant succession on recently deglaciated terrain in the Canadian High Arctic. *Journal of Biogeography*. 30: 277-296.

Jorgenson, J.C., J.M.V. Hoef and M.T. Jorgenson 2010a. Long-term recovery patterns of arctic tundra after winter seismic exploration. *Ecol. Appl 2*0: 205-221.

Jorgenson, J.C. and M.R. Joyce 1994. Six Strategies for Rehabilitating Land Disturbed by Oil Development in Arctic Alaska. *Arctic*. 47: 374-390.

Jorgenson, J.C., M.K. Raynolds, J.H. Reynolds and A.-M. Benson 2015. Twenty-Five Year Record of Changes in Plant Cover on Tundra of Northeastern Alaska. *Arctic, Antarctic, and Alpine Research*. 47: 785-806.

Jorgenson, M.T., J.G. Kidd, T.C. Carter, S. Bishop and C.H. Racine 2003. Long-Term Evaluation of Methods For Rehabilitation of Lands Disturbed by Industrial Development in the Arctic. *In* Social and Environmental Impacts in the North: Methods in Evaluation of Socio-Economic and Environmental Consequences of Mining and Energy Production in the Arctic and Sub-Arctic. R.O. Rasmussen and N.E. Koroleva, editors. Springer Netherlands, Dordrecht. 173-190.

Jorgenson, M.T., V. Romanovsky, J. Harden, Y. Shur, J. O'Donnell, E.A.G. Schuur, M. Kanevskiy and S. Marchenko 2010b. Resilience and vulnerability of permafrost to climate changeThis article is one of a selection of papers from The Dynamics of Change in Alaska's Boreal Forests: Resilience and Vulnerability in Response to Climate Warming. *Canadian Journal of Forest Research*. 40: 1219-1236.

Kearns, N.B., M. Jean, E.J. Tissier and J.F. Johnstone 2015. Recovery of Tundra Vegetation Three Decades after Hydrocarbon Drilling with and without Seeding of Non-Native Grasses. *Arctic*. 68: 16-31.

Kemper, J.T. and S.E. Macdonald 2009a. Directional change in upland tundra plant communities 20-30 years after seismic exploration in the Canadian low-arctic. *Journal of Vegetation Science* 20: 557-567.

Kemper, J.T. and S.E. Macdonald 2009b. Effects of Contemporary Winter Seismic Exploration on Low Arctic Plant Communities and Permafrost. *Arctic, Antarctic, and Alpine Research*. 41: 228-237.

Kevan, P.G. 1971. Vehicle Tracks on High Arctic Tundra. *Defence Research Board, Ottawa, Canada, Hazen*. 41.

Kevan, P.G., B.C. Forbes, S.M. Kevan and V. Behan-Pelletier 1995. Vehicle Tracks on High Arctic Tundra: Their Effects on the Soil, Vegetation and Soil Arthropods. *Journal of Applied Ecology*. 32: 655-667.

Kyhn, L.A., S. Wegeberg, D. Boertmann, P. Aastrup, J. Nymand and A. Mosbech 2020. Onshore Seismic Surveys in Greenland. Background information for preparation of Guidelines to Environmental Impact Assessment. Technical Report 161 from DCE - Danish Centre for Environment and Energy, Aarhus University.

Lamoureux, S.F., M.J. Lafrenière and E.A. Favaro 2014. Erosion dynamics following localized permafrost slope disturbances. *Geophysical Research Letters*. 41: 5499-5505.

Larcher, W. 1995. Physiological Plant Ecology. Springer Verlag,, Berlin. 506 pp.

Lawson, D.E. 1986. Response of Permafrost Terrain to Disturbance: A Synthesis of Observations from Northern Alaska, U.S.A. *Arctic and Alpine Research* 18: 1-17.

Matthews, J.A. and R.J. Whittaker 1987. Vegetation Succession on the Storbreen Glacier Foreland, Jotunheimen, Norway: A Review. *Arctic and Alpine Research* 19: 385-395.

McDowell, N.G., N.C. Coops, P.S.A. Beck, J.Q. Chambers, C. Gangodagamage, J.A. Hicke, C.-y. Huang, R. Kennedy, D.J. Krofcheck, M. Litvak, A.J.H. Meddens, J. Muss, R. Negrón-Juarez, C. Peng, A.M. Schwantes, J.J. Swenson, L.J. Vernon, A.P. Williams, C. Xu, M. Zhao, S.W. Running and C.D. Allen 2015. Global satellite monitoring of climate-induced vegetation disturbances. *Trends in Plant Science* 20: 114-123.

McKendrick, J.D. and W.M. Mitchell 1978. Fertilizing and Seeding Oil-Damaged Arctic Tundra to Effect Vegetation Recovery Prudhoe Bay, Alaska. 31: 296-304.

Michelsen, A., C. Quarmby, D. Sleep and S. Jonasson 1998. Vascular plant 15N natural abundance in heath and forest tundra ecosystems is closely correlated with presence and type of mycorrhizal fungi in roots. *Oecologia* 115: 406-418.

MRA 1987. Approval of A/S ARCO Greenlands plans for seismic winter surveys Jameson land 1987-88. Råstofforvaltningen for Grønland.

Mueller-Dombois, D. and H. Ellenberg 1974. Aims and methods of vegetation ecology. John Wiley & Sons, United States of America.

Myers-Smith, I.H., B.K. Arnesen, R.M. Thompson and F.S. Chapin 2006. Cumulative impacts on Alaskan arctic tundra of a quarter century of road dust. *Écoscience* 13: 503-510.

Müllerová, J., M. Vítková and O. Vítek 2011. The impacts of road and walking trails upon adjacent vegetation: Effects of road building materials on species composition in a nutrient poor environment. *Science of The Total Environment*. 409: 3839-3849.

Mølgaard, P. 1982. Temperature Observations in High Arctic Plants in Relation to Microclimate in the Vegetation of Peary Land, North Greenland. *Arctic and Alpine Research* 14: 105-115.

Møller, M. and B. Strandberg 1991. Revegetation i Arktiske egne. Et litteratur review. B. Strandberg, editor. Grønlands Miljøundersøgelser, København.

Northwest-Territories, G.o.t. 2015a. Guidelines for safe ice construction D.o. Transportation, editor. Government of the Northwest Territories.

Northwest-Territories, G.o.t. 2015b. Northern Land Use Guidelines Northwest Territories Seismic Operations. D.o. LAnds, editor, Yellow Knife.

Nuna-Tek 1989. Klima. Jameson Land, Del 1 og Del 2.

Obu, J., S. Westermann, A. Bartsch, N. Berdnikov, H.H. Christiansen, A. Dashtseren, R. Delaloye, B. Elberling, B. Etzelmüller, A. Kholodov, A. Khomutov, A. Kääb, M.O. Leibman, A.G. Lewkowicz, S.K. Panda, V. Romanovsky, R.G. Way, A. Westergaard-Nielsen, T. Wu, J. Yamkhin and D. Zou 2019. Northern Hemisphere permafrost map based on TTOP modelling for 2000–2016 at 1 km2 scale. *Earth-Science Reviews* 193: 299-316.

Olsson, P.A., B. Eriksen and A. Dahlberg 2004. Colonization by arbuscular mycorrhizal and fine endophytic fungi in herbaceous vegetation in the Canadian High Arctic. *Canadian Journal of Botany*. 82: 1547-1556.

Pearce, A.R., E.B. Rastetter, B.L. Kwiatkowski, W.B. Bowden, M.C. Mack and Y. Jiang 2015. Recovery of arctic tundra from thermal erosion disturbance is constrained by nutrient accumulation: a modeling analysis. *Ecol. Appl 2*5: 1271-1289.

R. McManus Consulting Ltd., Integrated Environments Ltd. and S.C. Inc. 2004. Evolving approaches to minimize the footprint of the Canadian oil and natural gas industry.

Raynolds, M.K., D.A. Walker, K.J. Ambrosius, J. Brown, K.R. Everett, M. Kanevskiy, G.P. Kofinas, V.E. Romanovsky, Y. Shur and P.J. Webber 2014. Cumulative geoecological effects of 62 years of infrastructure and climate change in ice-rich permafrost landscapes, Prudhoe Bay Oilfield, Alaska. *Global Change Biology* 20: 1211-1224.

Schmugge, T.J., Kustas, W.P., Ritchie, J.C., Jackson, T.J., and A. Rango 2002. Remote sensing in hydrology. *Advances in Water Resources* 25 (8–12): 1367-1385

Seburn, D.C. and G.P. Kershaw 1997. Changes in the active layer of a subarctic right-of-way as a result of a crude-oil spill. *Canadian Journal of Earth Sciences*. 34: 1539-1544.

Semerdjieva, S.I., E. Sheffield, G.K. Phoenix, D. Gwynn-Jones, T.V. Callaghan and G.N. Johnson 2003. Contrasting strategies for UV-B screening in sub-Arctic dwarf shrubs. *Plant, Cell & Environment* 26: 957-964.

Shaver, G.R. and J.C. Cutler 1979. The Vertical Distribution of Live Vascular Phytomass in Cottongrass Tussock Tundra. *Arctic and Alpine Research* 11: 335-342.

Shiklomanov, N.I., D.A. Streletskiy and F.E. Nelson 2012. Northern Hemisphere Component of the Global Circumpolar Active Layer Monitoring CALM Program. *In* Tenth International Conference on Permafrost. Vol. 1. K.N. Hinkel, editor, Salekhard, Russia.

Sparrow, E.B., C.V. Davenport and R.C. Gordon 1978. Response of Microorganisms to Hot Crude Oil Spills on a Subarctic Taiga Soil. *Arctic*. 31: 324-338.

State-of-Alaska 2013. Mitigation Measures and Lessee Advisories. Alaskas Department of Natural Resources, editor. Division of Mining, Land and Water, Alaska.

State-of-Alaska 2015. Off-road travel on the North Slope on State Island. A.D.o.N. Ressources, editor. Division of Mining, Land and Water.

State-of-Alaska 2018. Snow sampling requirements. Ice road Construction and winter off-road travel. D.o.N. Resources, editor. Division of Mining, Land & Water, Northern Regional Office, Alaska.

Streever, J., J. McKendrick, L. Fanter, S.C. Anderson, J.G. Kidd and K.M. Portier 2003. Evaluation of percent cover requirements for revegetation of disturbed sites on Alaska's North Slope. *Arctic*. 56: 234-248.

Těšitel, J., T. Těšitelová, A. Bernardová, E.J. Drdová, M. Lučanová and J. Klimešová 2014. Demographic population structure and fungal associations of plants colonizing High Arctic glacier forelands, Petuniabukta, Svalbard. *Polar Research*. 33: 20797.

Thingvad, N. and H. Søgaard 1984. Sneforholdene i Jameson Land. April 1984. *GTO. Københavns Universitet*: 41 pp.

Ulrich, A. and P.L. Gersper 1978. Plant Nutrient Limitations of Tundra Plant Growth. *In* Vegetation and Production Ecology of an Alaskan Arctic Tundra. L.L. Tieszen, editor. Springer New York, New York, NY. 457-481.

Vavrek, M.C., N. Fetcher, J.B. McGraw, G.R. Shaver, F.S. Chapin and B. Bovard 1999. Recovery of Productivity and Species Diversity in Tussock Tundra Following Disturbance. *Arctic, Antarctic and Alpine Research*. 31: 254-258.

Walker, D., D. Cate, J. BROWN and C. Racine 1987. Disturbance and recovery of Arctic Alaskan tundre terrain: A review of recent investigations.

Walker, D.A. 1997. Arctic Alaskan vegetation disturbance and recovery. *In* Disturbance and recovery in Arctic lands. R.M.M. Crawford, editor. Kluwer Academeic Publishers, Netherlands. 457-479.

Walker, D.A. and K.R. Everett 1987. Road Dust and its Environmental Impact on Alaskan Taiga and Tundra. *Arctic and Alpine Research* 19: 479-489.

Walker, D.A., G.J. Jia, H.E. Epstein, M.K. Raynolds, F.S. Chapin III, C. Copass, L.D. Hinzman, J.A. Knudson, H.A. Maier, G.J. Michaelson, F. Nelson, C.L. Ping, V.E. Romanovsky and N. Shiklomanov 2003. Vegetation-soil-thaw-depth relationships along a low-arctic bioclimate gradient, Alaska: synthesis of information from the ATLAS studies. *Permafrost and Periglacial Processes* 14: 103-123.

Walker, D.A., M.T. Jorgenson, M. Kanevskiy, A.K. Liljedahl, M. Nolan, M.K. Raynolds and M. Sturm 2019. Likely impacts of proposed 3D-seismic surveys to the terrain, permafrost, hydrology, and vegetation in the 1002 Area, Arctic National Wildlife Refuge, Alaska. Alaska Geobotany Center Publication AGC 19-01. University of Alaska Fairbanks, Fairbanks, Alaska, USA.

Walker, D.A., M.K. Raynolds, F.J.A. Daniëls, E. Einarsson, A. Elvebakk, W.A. Gould, A.E. Katenin, S.S. Kholod, C.J. Markon, E.S. Melnikov, N.G. Moskalenko, S.S. Talbot, B.A. Yurtsev and T.o.m.o.t.C. Team 2005. The Circumpolar Arctic vegetation map. *Journal of Vegetation Science* 16: 267-282.

Walker, D.A., P.J. Webber, K.R. Everett and J. Brown 1978. Effects of Crude and Diesel Oil Spills on Plant Communities at Prudhoe Bay, Alaska, and the Derivation of Oil Spill Sensitivity Maps. *Arctic*. 31: 242-259.

Wallroth T, L.H., Rimsa A 2010. The Greenland Analogue Project (GAP). Literature review of hydrogeology / hydrogeochemistry. *Svensk Kärnbränslehantering AB. Swedish Nuclear Fuel and Waste Management Co.*

Waring, R.H. and S.W. Running 2007. Chapter 3-Carbon Cycle. *In* Forest Ecosystems. Academic Press, San Diego, CA, USA, 59-98.

Wegeberg, S. and D. Boertmann 2016. Disko Island and Nuussuaq Peninsula, West Greenland. A strategic environmental impact assessment of petroleum exploration and exploitation. Scientific Report from DCE 108, Danish Centre for Environment and Energy, Aarhus University.

Wein, R.W. and L.C. Bliss 1973. Experimental Crude Oil Spills on Arctic Plant Communities. *Journal of Applied Ecology*. 3: 671-682.

Williams, T.J., W.L. Quinton and J.L. Baltzer 2013. Linear disturbances on discontinuous permafrost: implications for thaw-induced changes to land cover and drainage patterns. *Environmental Research Letters*. 8.

Yukon-Government 2006. Best oil and gas management practices - Seismic exploration, Yukon.

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– with recommendations for best practices to minimize vegetation damage from driving with heavy equipment

This report describes the potential environmental impacts from surveying with heavy vehicles in Arctic areas (Canada, Alaska, Greenland), the environmental regulation in these areas and lessons learned from seismic surveying in Jameson Land, East Greenland in the 1980ies.

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