LITERATURE REVIEW OF PERMAFROST IN NORTHERN ALASKA PARKS, 2012

FINAL REPORT

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INTRODUCTION

DEFINITION OF PERMAFROST

Permafrost is defined as soil, rock, ice, and/or organic material that remains at or below 0 °C for at least two consecutive years. The depth of permafrost varies, but can reach depths of tens to hundreds of meters (French 2007). In the areas of Alaska where permafrost is present, the typical depth is 25 to 90 meters, but can vary from 0 to 200 meters (Ferrians 1965, Brown et al. 1993). Permafrost is found at high latitudes but can also exist at lower latitudes at high elevations. Permafrost can contain variable amounts of water and water does not need to be present for permafrost to form. Ice-rich permafrost contains more than 50% frozen water (Williams and Smith 1991). Ice-poor permafrost contains little or no frozen water, however the soil remains at a temperature less than 0ºC.

AREAS OF PERMAFROST

Areas where permafrost exists can be organized into four groups: continuous, discontinuous, sporadic, and isolated (Brown et al. 1993). In areas of continuous permafrost, more than 90% of the landscape is underlain by permafrost, the mean annual ground temperature is typically colder than -6 °C (Osterkamp and Jorgenson 2009) and un-frozen zones may exist beneath lakes and river channels. In discontinuous permafrost regions, areas of unfrozen ground separate frozen ground and between 50 to 90% of the landscape is underlain by permafrost (Heginbottom et al. 1993). Sporadic permafrost covers 10% to 50% and isolated permafrost covers <10% of the landscape. Sporadic and isolated permafrost is usually found beneath peaty organic sediments (French 2007). Permafrost can also exist in alpine areas at lower latitudes in dry-continental environments (French 2007).

Eighty percent of Alaska is underlain by permafrost, with 32% continuous, 31% discontinuous, 8% sporadic, and 10% isolated permafrost. Glaciers and ice sheets comprise 4% of Alaska (Jorgenson et al. 2008b, French 2007). Continuous permafrost in Alaska is generally found from the Brooks Range northward. Discontinuous permafrost is predominant from the southern foothills of the Brooks Range to the Alaska Range. Sporadic and isolated permafrost is found south of the Alaska Range, Talkeetna, and Wrangell Mountains (Brown et al. 1993, Hinzman et al. 2004).

Continuous permafrost underlies the following Arctic Network Parks, Preserves, and

Monuments: Gates of the Arctic National Park and Preserve (GAAR), Noatak National Preserve (NOAT), Kobuk Valley National Park (KOVA), Bering Land Bridge National Preserve (BELA), and Cape Krusenstern National Monument (CAKR). Discontinuous permafrost underlies the Central Alaska Network Parks and Preserves including Denali National Park and Preserve (DENA), Wrangell-St. Elias National Park and Preserve (WRST), and Yukon-Charley Rivers National Preserve (YUCH). This discontinuous permafrost is “warm” and typically within a few degrees of thawing (Osterkamp 1983, Osterkamp 1994, Osterkamp 2005, Osterkamp 2007).

PERMAFROST FORMATION

The formation of permafrost depends primarily on the surface air temperature, but is influenced by soil moisture content, soil/rock type, depth of snow cover, aspect, and the presence of vegetation. The southern limit of continuous permafrost corresponds with a mean annual air temperature of approximately -8 °C and the southern limit of discontinuous permafrost corresponds with a mean annual air temperature of -1 °C (Barry 2011).

The moisture content of soils can determine the presence of permafrost by providing different levels of thermal conductivity. Wet, frozen soils have greater thermal conductivity and allow permafrost to exist in areas where permafrost would otherwise be absent (Davis 2001). Dry soils, with low thermal conductivity, can insulate permafrost and help maintain it during the summer months (Ferrians 1994). The albedo and thermal conductivity of soil and rock type also plays a part in the presence of permafrost; soils with a high albedo and high thermal conductivity can absorb thermal radiation and can allow heat to penetrate to depth (French 2007, Davis 2001).

Deep snow inhibits permafrost development by providing insulation from the cold winter temperatures. Snow cover can vary due to topography, wind direction, and vegetation. Areas of permafrost tend to be found where high winds and/or limited snowfall allow soils to be exposed to winter cold (French 2007). These microclimates, governed by local topographical features, determine the presence of permafrost in areas where the mean annual air temperature is near freezing. If snow persists late into spring, ground thawing will be delayed. The timing of snowfall also affects permafrost development. Low winter snowfall amounts increase the extent of penetration of winter cold. Heavy autumn snowfall decreases the extent of winter cold penetration (French 2007). The pattern of seasonal snow cover is the controlling factor in distribution of permafrost in discontinuous zones; areas with thick snow cover show an absence of permafrost whereas permafrost may exist in areas where snow does not accumulate (French 2007, Granberg 1973, Nicholson and Thom 1973). In continuous permafrost regions, the snow cover has an insulating effect and results in the active layer being thickest at upland localities (French 2007).

In hilly or mountainous areas, aspect plays an important part in the presence of permafrost. South-facing slopes receive more solar radiation and are often free of permafrost; north-facing slopes are often underlain by permafrost (Ferrians 1994, Hinzman et al. 2004).

Vegetation provides additional variation to the presence of permafrost through shielding the underlying soils and/or permafrost from solar heat (French 2007, Viereck 1965). Dry soils with no vegetation can have higher temperatures than wet soils with vegetation present, often by several degrees (Ferrians 1994). Winter cold penetrates more deeply in boreal forest and taiga regions where trees shade underlying soils and catch snowfall (French 2007, Viereck 1965). Isolated trees can provide an opportunity for isolated permafrost bodies to exist in areas not conducive to permafrost formation (Viereck 1965).

THE ACTIVE LAYER

The topmost layer of permafrost undergoes seasonal flux. This flux earns this layer the name, "the active layer" because it is subject melting in the summer and re-freezing in the winter. The active layer is thinnest (~15 cm) in polar regions and thickest (greater than 1 meter) in sub-arctic regions (French 2007). Active layer thickness varies from year to year and is dependant on air temperature, slope orientation and angle, ecological succession, disturbance history (e.g., fire), drainage, snow cover, soil and/or rock type, and water content.

In areas of continuous permafrost, the active layer generally extends all the way to the permafrost layer (French 2007). In areas of discontinuous permafrost, the active layer can be separated from the top of the permafrost layer by a "talik" (Williams and Smith 1991). The active layer may not re-freeze completely during the winter. In this event, an unfrozen section, or talik, forms between the permafrost below and the active layer above. Groundwater movement is restricted to taliks due to the impermeable nature of permafrost.

The depth of the active layer is determined by vegetation and topography. Plants provide insulation from summer temperatures, minimizing the depth of the active layer thaw (French

2007). Conversely, plant roots cannot penetrate beyond the active layer, limiting the vegetation to plants with shallow root systems (Benninghoff 1952). Plants with deeper root systems, such as conifers, can be found in areas of discontinuous permafrost (Benninghoff 1952). The frozen ground beneath the active layer is less pervious to water, which leads to a marsh-like environment during summer months (Davis 2001).

DEFINITION OF THERMOKARST

Thermokarst is ground subsidence, collapse, erosion, and ground surface instability caused by the thawing of permafrost (Osterkamp et al. 2000, Jorgenson et al. 2001, Jorgenson and Osterkamp 2005, French 2007). Thermokarst terrain has been observed in Alaska (Osterkamp 1995, Osterkamp et al. 2000, Jorgenson et al. 2001). Soil texture is related to the extent of settling upon permafrost thawing. Gravelly, well-drained soils have low ice content and show little or no settlement when thawed. Conversely, silty soils often have high ice contents and settle a meter or more upon thawing (Jorgenson and Osterkamp 2005). Soils previously supported by permafrost will collapse when they thaw, creating marshy hollows and small hummocks. Water from melting permafrost or precipitation can collect in these depressions creating thermokarst lakes. The impervious permafrost below the lakes usually prevents drainage but if there is continued melting of the permafrost, lake drainage can result.

The formation of thermokarst can create various thermokarst-specific features:

> Beaded streams: Beaded streams are a product of melting ice-wedge polygons that are characterized by sharply defined pools of water at the intersections of the polygons and interconnected with short drainage channels formed by the edges of the polygons (Davis 2001). Channel enlargement results in the formation of beaded streams at the intersections of ice wedges (French 2007).
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> Thermokarst lakes: These bodies of water are also known as thaw lakes, tundra lakes, and tundra ponds. All of these names are used to describe areas of subsidence that have filled with water. The water in these areas comes from the previously existing permafrost or from snowmelt. The evolution of thaw lakes is rapid and lateral bank erosion ranges from 15 to 25 cm per year (French 2007).

Thermokarst depressions: Thermokarst depressions are areas where thermokarst lakes previously existed, but have now evaporated or drained. Overlapping depressions suggest a rapid and progressive evolution of thaw lakes; this evolution involves initiation, expansion, capture of other lakes, and drainage (French 2007)

Drunken forests: Drunken forest are tilted spruce trees, whose tilt has resulted from the aggradation and/or degradation of ice rich permafrost (Kokelji and Burn 2003). One cause of tilting is annual frost heave and settlement of the active layer; another is post-fire thinning of the active layer, which causes the overlying ground to heave.

Talik: Taliks are unfrozen areas of soil found between sections of frozen soil or between the permafrost and active layer (Riordan 2005). Talik growth is influenced by increased temperature of adjoining ground and/or water bodies. Merging of neighboring taliks create paths for water drainage and may allow for standing water to be dispersed by sub-surface drainage (Yoshikawa and Hinzman 2003, Riordan 2005).

Gelifluction lobes (soil flowing downslope): Gelifluction is the flow of soil in association with frozen ground (Washburn 1973). Water is unable to penetrate below the permafrost table when thawing occurs. On slopes between 5% and 20% gradient, the saturated or nearly-saturated soils lose friction and cohesion and behave like a viscous fluid. Near-vertical scarps mark the downslope fronts of the lobes and can reach heights of six feet (Boggs and Michaelson 2001).

Active-layer detachments (ALDs): ALDs occur when the thawing active layer forms a slurry at the boundary between the ice-rich permafrost and the active layer. The surface layer moves as a whole, is held intact by the root mat, and is deposited downslope. ALDs leave behind bare soil, which is prone to erosion, or ground ice, which is prone to melting (Gooseff et al. 2008, Lamoureux and Lafrenière 2009, Swanson and Hill 2010). ALDs may be 1 to 10 meters wide and hundreds of meters long (Davis 2001). The depths of these detachments range from 0.5 to 1 m below the surface. ALDs can be caused by unusually rapid snowmelt, unusually heavy summer rainfall, or as a post-fire phenomenon. The warming climate increases fire frequency and severity of ALDs (Jorgenson and Osterkamp 2005). Erosion of soils exposed by ALDs can cause sedimentation of nearby water bodies (Jorgenson and Osterkamp 2005).

> Retrogressive thaw slumps (RTSs): RTSs are caused by the cut-bank of a stream or lake advancing into undisturbed ground. Material in the steep bank thaws, slumps, and falls and is partially carried away by water erosion (Crosby 2009a, Crosby 2009b). An RTS can encompass an area over 1 ha and reach depths of several meters, thus displacing large volumes of sediment (Swanson 2010). This sediment displacement results in the exposure of extensive areas of bare soil (Swanson 2010). Considerable numbers of RTSs have been identified in ARCN (Balser et al. 2007, Swanson and Hill 2010, Swanson 2010).

AREAS OF THERMOKARST IN ALASKA

Aerial imagery shows that 5% of the area in the discontinuous permafrost zone in Alaska contains thermokarst features while thermokarst features cover 13.5% of the continuous permafrost zone (Jorgenson et al. 2008b). In study sites, areas affected by thermokarst have increased by 3.5% to 8 % over the past 50 years (Jorgenson et al. 2008b).

PERMAFROST AND CLIMATE CHANGE

Thermokarst subsidence can alter ecosystems and even result in the conversion of one kind of ecosystem into another (Van Cleve and Viereck 1983, Burn 1998, Osterkamp et al. 2000, Jorgenson et al. 2008a). For example, the thawing of permafrost can cause a terrestrial system to transform to an aquatic or wetland system. Conversely, an aquatic or wetland system can transform to a terrestrial ecosystem as a result of thermokarst lake drainage (Jorgenson et al. 2001; Karle and Jorgenson 2004). If climate warming continues as predicted, recent models indicate that 10% to 17% of the permafrost area may thaw (Anisimov and Nelson 1996), although permafrost at the deepest levels may not completely disappear (Jorgenson and Osterkamp 2005).

The loss of underlying permafrost can also allow for increased drainage of wetland systems (Jorgenson et al. 2008a). These changing soil moisture conditions allow new plant species to grow (Schuur et al. 2007). The size, abundance, and distribution of aquatic resources are also affected by the distribution of permafrost. Thawed permafrost soils have increased water-holding capacity, which can lead to reduced lake levels (Loso et al. 2007). Thawing permafrost effects stream and lake hydrology by altering stream flow, sediment deposition/erosion rates, and stream temperatures (Oswood et al. 1992, Osterkamp 2005).

The expansion of tall, woody plant communities into areas of thawing permafrost is expected (Lloyd et al. 2003). This expansion could lead to increased snowpack, greater insulation of the ground, and thus result in an acceleration of permafrost degradation (Lloyd et al. 2003).

PERMAFROST AND FIRE

After wildland fires, permafrost ground warms and the active layer thickens until the plant cover grows back. Fire increases long-term soil temperatures in three ways: it removes insulating organic surface layers, it changes albedo through surface blackening, and removes shade from vegetation canopies (Dyrness et al. 1986). The darkened surfaces from charred vegetation also contribute to permafrost thaw (French 2007).

The speed of fire and moisture in the soil and vegetation determines the effect on permafrost. Quick moving fires in areas of moist underlying vegetation (peat, moss, lichens) have minimal effect on permafrost (Yoshikawa et al. 2003, Swanson 1996). Direct soil heating caused by fire is thought to be negligible due to thick, moist forest floor layers (Dyrness et al. 1986). This is supported by minimal soil temperature changes recorded before and after experimental fires in spruce/feathermoss stands (Viereck and Schandelmeier 1980). Slower moving fires and exceptionally dry vegetation have both short and long term effects. Short-term effects include the thawing of ice-rich soils, increased erosion, and the development of active layer detachments. Long-term effects include the increase in active layer depth, permafrost degradation, and slope instability (Burn 1998, French 2007).

It is estimated that is takes 25 to 50 years after a fire event for the active layer to return to the original depth; spruce and feathermoss need this interval to restablish themselves (Van Cleve and Viereck 1983). In one instance, fire in an open black spruce stand caused deep thawing, with a maximum thaw depth of 302 cm. The evidence was observed 24 years after the fire (Viereck et al. 2008).

PERMAFROST AND CARBON STORAGE

Approximately 900 gigatons (Gt) of carbon is estimated to be stored in permafrost soils worldwide (Zimov et al. 2006). Increased thaw of organic matter contained in permafrost and its subsequent decomposition will release carbon as CO_2 and CH_4 (French 2007). The mode of carbon release depends on the water content of soil; carbon in wet organic matter will be released primarily as CH_4, whereas dry organic matter will release CO_2 (Barry 2011). Methane release through ebullition (bubbling) has been observed in northern lakes (Kessler et al. 2012). Permafrost thaw beneath or adjacent to bodies of water will show an increase in the total organic carbon and total inorganic carbon in these water bodies. Thermokarst lakes have been implicated in releases of methane produced by the breakdown of organic matter that was previously sequestered in permafrost (Walter 2007). Carbon release from thawing permafrost could lead to further climate warming, creating a cycle of increasing warmth leading to more carbon release, increasing warmth, etc. (Walter et al. 2006).

PERMAFROST AND MERCURY STORAGE

In addition to carbon storage, the organic matter in permafrost has been shown to trap mercury (Rydberg et al. 2012). It is important to understand the sources of Hg for geopolitical reasons; Hg transported to wetlands is methylated into highly toxic MeHg, which can bioaccumulate. A major source of anthropogenic mercury is the burning of coal while natural sources of mercury are volcanic and mantle degassing (Shotyk et al. 2005).

While the cold Arctic climate does not favor mercury deposition, lake sediments containing mercury show fluxes that may have increased over the past 100 years. The study into the topic concluded that there was no significant evidence that climate change has affected these rates of atmospheric deposition (Shotyk et al. 2005). Once permafrost is thawed, contaminants such as mercury are available to be released into Arctic lakes (Rydberg et al. 2012).

PERMAFROST LITERATURE OF ARCTIC NETWORK (ARCN) PARKS

NOATAK NATIONAL PRESERVE (NOAT)

Swanson and Hill (2010) studied 24 selected retrogressive thaw slumps using oblique aerial photographs, which were used to create high-resolution three-dimensional topographic models with photographic overlay. Twenty-two slumps were located in NOAT and two were located in Gates of the Arctic National Park and Preserve (GAAR). These photos and models will be used to track the rate of growth or stabilization of the slumps, the volume of material displaced, and the rate of re-vegetation of the affected areas. The purpose of the study is to determine the rates of growth, stabilization, and re-vegetation as well as to determine influencing factors such as ground ice type, geological setting, and weather.

Slumps exposed both ground ice and soil and ranged up to 4 ha in extent with main scarps ranging from 2 to 10 meters. A subset of the study slumps that were previously photographed aerially in 1980 were observed to have expanded slightly and been subsequently re-vegetated. Five of the 22 of slumps that were surveyed in NOAT were found to be advancing through previous slump areas. Main scarps of the study slumps were found to have incised an additional 100 to 300 meters in 30 years or less.

Field investigations by Balser et al. (2009), augmented by photogrammetric measurements, reveal thermokarst failure types such as active layer detachments, thermokarst gullies, and retrogressive thaw slumps in NOAT. By comparing 2006 imagery with historical photographs, a two-fold increase in the number of thermokarst features and the total surface area of affected landscape was observed over 25 years. Many new thermokarst features were found in the Noatak headwaters region; the authors suggest that thermokarst may be greatly under-reported in other permafrost regions due to the difficult logistics associated with remote area surveys.

Racine et al. (2006) investigated vegetation change following tundra fires in NOAT. Eight fire plots (some were established as early as 1982) have been re-measured and relocated to monitor the effects of fire disturbance on vegetation cover. Other sites included in the monitoring program included one site burned in 1972 and four sites burned in 1977. The plots described in Table 1 were located near Noatak River (NOAT 3), Kungiakrok Creek (KUNG), Uchugrak Hills (UCHG), and the Kugururok River (KUGUR). Vegetation cover was observed, and thaw depths were measured at five points in each plot.

The percent cover of vascular plants increased significantly in the plots burned in 1977 and 1982 (See Table 1). Most of the vascular plants consisted of shrubs (willows, birch). Plant types that decreased or disappeared include grasses and forbs. Deciduous and evergreen shrubs expanded on NOAT1. Deciduous shrubs, forbs, and sedges increased on NOAT2 and NOAT3. The grasses on NOAT3 disappeared. At the KUNG burn site, there was originally about 34% sedge cover, but by 2005 the sedge cover had expanded to about 70%. On the KUNG unburned site there was a decrease in sedge but an increase in grasses, deciduous shrubs, and evergreen shrubs. At the burned UCHG site, there was a 40% increase of vascular plants including sedges and deciduous shrubs. The unburned UCHG site showed little change, but there was already 70% vascular plant cover, which consisted of 45% to 50% shrubs. Lastly, the KUGUR site had an increase of deciduous shrubs and sedges. Evergreen shrubs became present when the plot was observed in 2005. Studying fire plots to assess fire disturbance is valuable, however further long-term monitoring will be needed in order to differentiate the effects of fire disturbance from those related to climate change.

Table 1: Percent change in cover of burned and unburned control sites (Racine et al. 2006).

Site	Fire Date	Vascular	Graminoids	Deciduous Shrubs	Evergreen Shrubs
NOAT 3	1977	+14	+10%	+18	nc
KUNG-B	1982	+51	+35 (sedge)	+10	+11
KUNG-U	na	+10	-15 (sedge)	+15	+11
UCHG-B	1977	+39	+4 (sedge)	+28	nc
UCHG-U	na	nc	+6 (sedge)	-8	nc
KUGUR-B	1972	nc	-23 (grass)	+11	+8

GATES OF THE ARCTIC NATIONAL PARK AND PRESERVE (GAAR)

Literature on permafrost in GAAR is quite sparse. The soil survey compiled by Boggs and Michaelson (2001) shows that the Kavachurak Foothills Subsection has continuous permafrost with low ice content, but permafrost is not addressed elsewhere in the survey. Swanson and Hill

(2010) included photos of two regressive thaw slumps located in GAAR and they created models to track the rate of growth or stabilization of the slumps.

BERING LAND BRIDGE NATIONAL PRESERVE (BELA)

Wetterich et al. (2012) investigated a unique sediment sequence was discovered when studying a pingo in the northern Seward Peninsula. Permafrost, which was formed in the Late Quaternary Period, kept fossils (fauna, flora, microbial communities) intact. Traces of *Picea* and *Larix* pollen were present indicating the presence of woodlands approximately 60 kya. It was considered a stadial or warmer period.

There were four sediment layers detected. The topmost layer is composed of early Holocene lake sediments. The next lowest layer is composed of late Wisconsin shallow water deposits. The following deeper layer is composed of late to mid-Wisconsin lake sediments; detritus and twig fragments were most common in this layer. The bottom layer identified in the pingo is composed of taberite of the early Wisconsin deposits. The study concluded that radiocarbon-dating revealed complex landscape interactions.

Parsekian et al. (2011) utilized remote sensing, ground penetrating radar, and field surveys to study floating vegetation mats in thermokarst lakes on the northern Seward Peninsula. The two sites in the study were Lake Rhonda and Lake Owl, which were considered later generation thermokarst lakes. Floating vegetation mats originate from the margins of the lake where portions of the active layer detach. They trap gas beneath the plant tissue and the resulting bubbles cause the mats to be buoyant. The presence of the floating mats keeps the water temperature underneath from freezing during the winter, which in turn causes talik and active layers to continue to grow, which leads to further expansion of the thermokarst feature.

Peat accumulation was measured in the northern Seward Peninsula by Jones et al. (2012). Remote sensing was used to determine the total organic carbon found in surface peat deposits. Measurements for terrestrial peat thickness, bulk density, organic matter content, and basal radiocarbon age from permafrost cores were also recorded.

Organic carbon, stored in permafrost, has been identified as being a vulnerable carbon source. Organic-rich and ice-supersaturated permafrost, in particular, releases larger amounts of carbon when it thaws. Peat, found in drained thermokarst lake basins, likely serves to slow carbon release. The Arctic Coastal Plain in northern Alaska consists of approximately 70 % lakes and basins. It was concluded that peat accumulates fastest in young basins but slows dramatically as the basin ages.

Changes in thermokarst lake extents, between 1950 and 2007, were studied in the northern Seward Peninsula by Jones et al. (2011). The study area was approximately 700 km^2. Remote sensing was the method used to quantify the changes among data sets from 1950 and 1951; 1978; and 2006 and 2007. The study categorized the thermokarst lakes into four size classes in hectares: 0.1 to 1.0, 1 to10, 10 to 40, 40 to 400. Thermokarst lakes, with an area of 0.1 to 1 ha and located in continuous permafrost, were increasing in abundance and in size throughout the study. The lakes with a surface area between 40 and 400 hectares were the least abundant and decreased in abundance throughout the study. Jones et al. concluded that the active expansion of thermokarst lakes was due to permafrost degradation; however, this same expansion increases the chance of drainage.

Three simulation experiments were performed by Kessler et al. (2012) on two thermokarst formations, Pear Basin and Lake Claudi, near Cape Espenberg in northern Seward Peninsula. Thermokarst lakes are important to study because they are major sources of atmospheric methane, and their release of methane can result in a positive feedback loop. The Cape Espenberg area consists of 73% thermokarst lakes and basins. The three simulations are the formation of Pear Basin, the formation of Lake Claudi, and the longterm evolution of Pear Basin and Lake Claudi.

Calibration of lake depth, morphology, methane production, and flow condition data was used to create the simulation on Pear Basin. Methane production, and compared simulated methane production and observed methane emissions data was used to create the simulation on Lake Claudi. It was concluded that more information on the soil parameters that control methane production is needed, and lake expansion and methane production are dependent on topography.

Utilizing satellite imagery from late June through early September 2006, Swanson (2010) identified 22 active layer detachments in BELA. The detachments exposed a total bare soil area of approximately 28,800 m^2. The largest detachment was 20 m wide and 200 m long. The permafrost in BELA is very ice-rich (up to 90% ice by volume) and can subside 20 m or more upon thawing (Shur et al. 2009). Retrogressive thaw slumps were not observed. The cause for the detachments was thought to be due to thawing from the exceptionally warm summer of 2004.

KOBUK VALLEY NATIONAL PARK (KOVA)

Swanson (2010) identified fourteen ALDs that exposed 16,200 m^2 of bare soil. The largest slide had dimensions of 300 m by 20 m, based on imagery from August 2008. Detachments showed some signs of re-vegetation. The detachments were found in the Salmon River Hills subsection, the Kunyanak Mountains subsection, and the Akiak Mountains subsection. Retrogressive thaw slumps were not observed. The cause for the detachments was thought to be due to thawing from the exceptionally warm summer of 2004.

CAPE KRUSENSTERN NATIONAL MONUMENT (CAKR)

Twenty-two active-layer detachments were identified in CAKR by Swanson (2010) using satellite imagery from 2006. Approximately 17,400 m^2 of bare soil was exposed from these slides. The largest detachment was 20 m wide and 200 m long. The detachments were all located in the Mulgrave Hills ecological subsection in the northern part of CAKR. Retrogressive thaw slumps were not observed. The cause for the detachments was thought to be due to thawing from the exceptionally warm summer of 2004.

PERMAFROST LITERATURE OF CENTRAL ALASKA NETWORK (CAKN) PARKS

DENALI NATIONAL PARK AND PRESERVE (DENA)

Yocum et al. 2007 undertook a baseline study of permafrost in the Toklat Basin of DENA and concluded that the area is underlain with both continuous and discontinuous permafrost. There were several characteristic features observed which include thermokarst depressions, thermokarst ponds, ice-wedge polygons, palsas, beaded streams, and drunken forests. It was common to observe standing water in the northern part of the basin because most of the soil found there was poorly drained (i.e. quaternary sediment). The southern half of the basin had soils that were described as well-drained. Thermokarst features were observed throughout the basin but the largest thermokarst was found in the southern half. Permafrost is a dominant geomorphic process in the basin, especially on its low-grade, north-facing slopes, because there is vegetation cover, small amounts of snow cover, and higher winds allowing colder temperatures to penetrate deeper into the soil.

Nearly 45% of the park (more than one million ha) has continuous (21%) or discontinuous (22%) permafrost. Approximately 14% of DENA's landscape has sporadic permafrost and 10% has no permafrost. The Alaska Range and environs were not classified (32%). Soils supporting stunted spruce or spruce woodlands over permafrost are abundant in the northwestern part of Denali. Permafrost also dominates the Toklat River Basin in northeastern portion of the park.

A study was performed in the northern portion of DENA by Roth et al. (2007) to assess the effectiveness of remote sensing. The two concerns of the study included determining the most cost-effective and accurate method for periodic land-cover classification and assessing the sensitivity of the mapping to seasonality. The study focused on several ground-based vegetation monitoring plots that were systematically placed.

Three types of satellite images classifications were compared for accuracy. These classifications include supervised spectral classification, unsupervised spectral classification, and photo-interpretation. Supervised spectral classification had a higher spectral resolution; however, this method was more time-consuming. It was concluded that a 6-class map was most accurate at 80% accuracy. The assigned classes were: dwarf scrub, open broadleaf forest, open spruce forest, partially vegetated, tall alder scrub, and tussock and low scrub. The study states that the 6-class map only detects large changes.

Remote sensing was utilized by Riordan et al. (2006) to determine if the shrinking pond trend, occurring in the Seward and Kenai peninsulas, was occurring in nine sites of interior Alaska. The remote sensing imagery used in the study was from between 1950 to 2002. Nine sites were chosen, of which one was located in DENA. Eight of the nine sites are in areas of discontinuous permafrost, and one site in an area of continuous permafrost.

According this study, the Pacific Decadal Oscillation of 1977 resulted in the climate changing from a cold-moist climate to a hot-dry climate. This warming of the climate has caused a number of demonstrable changes. Shrinking ponds may be the initial signal of far more widespread changes in lowlands. Throughout the nine sites, there was a 4% to 31% decrease in pond area. All of the sites displayed a 5% to 54% decrease in the number of ponds. The DENA site showed a 4% decrease in pond surface area and a 5% decrease in the total number of ponds.

The patterns and rates of thermokarst lake and shore fen development in the discontinuous permafrost zone in Alaska were evaluated by Jorgenson et al. (2012). Gosling Lake in the Mud River region of DENA was studied along with Billy Lake (WRST) and Finger Lake, located in the Copper River Basin and the Koyukuk Flats, respectively. Data was collected from Billy Lake and Gosling Lake in 2005 and at Finger Lake in 2006.

A majority of the thermokarst lakes decreased in area during the study with 76 lakes that decreased in area and 48 lakes that increased. Aerial photography displayed an 18.7% to 17.8% decrease in thermokarst lake area and a 4.2% to 5.8% increase in shore fen coverage. Lakes that showed expansion (0.12 m/yr) had no fens present, while lakes that decreased (-0.06 m/yr) had shore fen present.

Karle and Jorgenson (2004) determined which remote-sensing technique(s) would be most suitable for long-term monitoring of the changes in permafrost regime in DENA, YUCH and WRST. The test area in Denali was just north of the Toklat River Basin (63º 49’ 30” N, 150º 07’ 00” W). There were seven types of remote sensing used: USGS black and white aerial photography, color aerial photography, color infrared photography, AHAP photography, LANDSAT, SPOT, and RADARSAT. After conducting the pilot scale analysis, it was concluded that high-quality low-level aerial photography would be practical for long-term monitoring of landscape changes and photo interpretation of imagery should be used to describe the extent of permafrost degradation.

Shur and Jorgenson (2007) created a classification system to help describe patterns in permafrost formation which result from climate and other ecological factors. Permafrost formation is complex and its formation differs between continuous and discontinuous areas. There were five patterns of formation: climate-driven; climate-driven, ecosystem-modified; climate-driven, ecosystem-protected; ecosystem-driven; and ecosystem protected. Climate-driven permafrost forms in cold to very cold areas and does so independent of the growth of vegetation. Climate-driven, ecosystem-modified permafrost forms in cold areas and the upper layer of permafrost is modified by ecosystem (vegetation) succession. Climate-driven, ecosystem protected permafrost was originally formed in very cold temperatures. This type of permafrost has unique cryostructures that are protected by the ecosystem, even in neutral climates. Ecosystem-driven permafrost formation is not driven solely by climate but is modified by other and complex ecological factors, including soil temperatures and wind speeds. Lastly, ecosystem-protected permafrost can persist under vegetation and ecosystem succession; however, it cannot form after there is a disturbance, such as fire or mechanical removal of vegetation.

A study area near Eight Mile Lake, which is located 14 km west of Healy, Alaska (63º 52' 42”N, 149º15' 12”W) is in close proximity to DENA. Literature from this site was deemed relevant to include in this literature survey and is included below.

Osterkamp et al. (2009) conducted field and remote sensing measurements at the Healy, Alaska to investigate how physical and ecological changes are linked to both the formation and degradation of permafrost. Air, ground, and permafrost surface temperatures have been measured since 1985 at depths of up to 30 meters. The permafrost at the study sites was classified at climate-driven, ecosystem-protected and it contained five types of cryostructures, including pore ice, lenticular ice, organic-matrix ice, ataxitic ice, and layered ice. Ground ice is important because its presence and abundance can determine whether or not thermokarst develops.

Vogel et al. (2008) also carried out research at the Healy, Alaska site. This study reached two fundamental hypotheses. The first was that if the rates of climate change in higher latitudes were to continue to increase, then the soil carbon pools would decrease and cause a large increase in atmospheric CO_2 levels. The second was that the continued warming would stimulate plant growth, which would then lead to faster carbon absorption rates than its release from thawing, resulting in a longer growing season.

Gas exchange was measured to gain insight into the effect that permafrost and thermokarst formation have on the overall carbon balance. Climate measurements were also measured to show the changes in temperature over a long period of time. It was concluded that CO_2 loss can be reversed after the initial thaw, unless the thawing is extensive. It only takes a couple of years (or less) for thermokarst formation to begin.

In 2007, Schuur et al. studied the warming effects on plant communities at three field sites at Eight Mile Lake to determine the direct temperature effects on plant growth and indirect effects via change of available soil nutrients. The three sites ranged from a relatively undisturbed site, a heavily disturbed site where permafrost was noted to have thawed around 1951, and an intermediate site where thawing was first observed in 1985. Plant biomass at the field sites ranged from graminoid-dominated at the least disturbed site, to shrub-dominated at the most disturbed site, and to a co-domination of graminoids and shrubs at the intermediate site. A trend in species composition change from sedges to shrubs was observed as thermokarst became more developed. It was observed that graminoids preferred cold, dry microsites while moss and shrubs preferred warm, moist microsites. This data supports the apparent decrease in graminoids as thermokarst becomes more prevalent. Measurements of total nitrogen (N) in plants at each of three sites showed higher total canopy N values for the two sites that show signs of thermokarst. This suggests that permafrost thawing creates an increase in the supply rate of N from the soil.

Lee (2009) investigated CO_2 production at the three field sites above to examine the relationship between permafrost thaw and thermokarst development and CO_2 flux from various soil depths. Gas samples from varying depths (5 to 40 cm, in 5 cm increments) were taken from May to September from 2005 to 2007. Samples were not taken from soil until the active layer depth exceeded the sampling depth. Ninety percent of CO_2 released from the active layer was observed to originate from the 5 to 25 cm depth. CO_2 production from the 20 to 30 cm layer was equivalent among the three sites, which suggests that organic matter decomposition in deeper layers does not play a significant role in CO_2 release. The mean active layer depth at all three sites over the time of the study was 32 cm. Production of CO_2 increased in areas of greater thermokarst development. Soil temperature at thermokarst depressions was higher than in uneffected areas.

WRANGELL-ST. ELIAS NATIONAL PARK AND PRESERVE (WRST)

Soils in areas underlain by permafrost are susceptible to damage and permafrost thawing by off-road vehicle (ORV) use. Arp and Simmons (2012) investigated the impacts of off-road vehicles on watersheds and soils underlain by permafrost in WRST.

Aerial photography was used from several years (1957, 1981, 2004) to determine the extent of ORV damage to permafrost soils. Ground studies from 2009 were also used to compare with the images. ORV use in lowlands can damage the soils as well as alter the landscape and watershed processes. The study focused on trails in the northwest portion of the park, which were along the intermountain lowlands. It was concluded that pronounced effects occurred in low relief areas.

Human land use and climate change cause both short and long-term responses in permafrost and watershed processes alike. Some effects caused by ORV use include denudation of vegetation cover, increased active layer depth, and ground subsidence. If trail use is extensive then erosion, thaw subsidence, and ponding water can result. If the trails are in a degraded condition, ORV use may begin to stray from the trail, which in turn increases the area being altered and impacted.

Racine and Ahlstrand (1991) investigated the impact of ORV traffic in a test site located along the northern edge of WRST between Slana and Nabesna. One hundred and forty test lanes were established, each with an assigned vehicle, traffic intensity, and traffic timing. The change in thaw depth depended on the traffic pattern, time during the thaw season, and vehicle tested.

Remote sensing was used by Shur and Jorgenson (2007) to determine if the shrinking pond trend occurring in the Seward and Kenai peninsulas was occurring in nine sites of interior Alaska. The remote sensing imagery used in the study was from between 1950 to 2002. Of the nine sites, one was located along the Copper River Basin in WRST. Eight of the nine sites were in areas of discontinuous permafrost, and one site in an area of continuous permafrost.

As stated previously, the Pacific Decadal Oscillation of 1977 resulted in the climate changing from a cold-moist climate to a hot-dry climate. The resulting warmer climate has caused several changes, especially the shrinking of the ponds. Throughout the nine sites, there was a 4% to

31% decrease in pond area. All of the sites also displayed a 5% to 54% decrease in the number of ponds.

The patterns and rates of thermokarst lake and shore fen development in the discontinuous permafrost zone in Alaska were evaluated by Jorgenson et al. (2012). Billy Lake in the Copper River Basin of WRST was studied along with Gosling Lake (DENA) and Finger Lake, located in the Mud River region and the Koyukuk Flats, respectively. Data was collected from Billy Lake and Gosling Lake in 2005 and at Finger Lake in 2006.

As previously stated in the DENA section, the majority of the thermokarst lakes decreased in area during the study. There were 76 lakes that decreased, and 48 lakes that increased. Aerial photography displayed a 17.8% to 18.7% decrease in thermokarst lake area and a 4.2% to 5.8% increase in shore fen coverage. Lakes that showed expansion (0.12 m/yr) had no fens present, while lakes that decreased (-0.06 m/yr) had shore fen present.

Roach et al. (2011) conducted a study to distinguish the mechanisms responsible for the heterogeneous trends in the fifteen closed-basin lake pairs in Alaska. There were three mechanisms that were considered to explain why certain thermokarst lakes' area was being reduced. Those mechanisms include taliks beneath the lake, surface water evaporation exceeding water inputs, and floating mat vegetation encroachment on a lake's surface. There were three mechanisms that were considered to explain why certain thermokarst lakes' area was not decreasing. Those mechanisms include subpermafrost groundwater recharge, stable permafrost, and thermokarst.

The authors concluded that non-decreasing lakes were deeper with a lower surface area to volume ratio, while decreasing lakes were shallower and had a larger surface area to volume ratio. It was thought that areas with ice-poor permafrost would be dominated by the shallow thermokarst lakes. These shallow lakes might also be more susceptible to losses in area, which is a result of terrestrialization. The results from the study indicate that the most probable scenario was terrestrialization as the mechanism for lake areas that were reducing combined with thermokarst as the mechanism for lake area that was not reducing.

Osterkamp et al. (2000) implemented study sites in discontinuous permafrost area, were studied to determine how boreal forest ecosystems respond to the degradation of ice-rich permafrost and thermokarst development. There were several sites located in valleys and upland areas, including the Mentasta Pass area located NE of WRST, the University of Alaska (UAF) campus, and Tanana River Valley sites. The impacts on boreal forest depend on the type and amount of ice present and the drainage conditions of the area. In general, ice-rich permafrost degradation can completely destroy the forest ecosystem above it.

A variety of thermokarst terrain and formations occurred at each site. Wet sedge meadows, bogs, thermokarst ponds and lakes were replacing forests in the Mentasta Pass area. The lakes were formed as a results of ice-rich permafrost thaw; the lakes were found to be up to three meters deep and having eroding banks up to 3 meters high. Thermokarst pits were up to a meter deep and some were filled with water. Ice lenses were also present in the area, and are one of the reasons for Mentasta Pass's largely affected area. The boreal forest in this area were being destroyed and converted into wet sedge meadows covering up to 10 ha.

The remote-sensing technique(s) testing site for Karle and Jorgenson (2004) in WRST was located east of the Chetaslina River roughly centered at 61º 51' 00" N, 144º 40' 00" W. Please see the DENA section for full details.

YUKON-CHARLEY RIVERS NATIONAL PRESERVE (YUCH)

Information on permafrost status in YUCH is very sparse. Swanson (2001) outlined the presence and type of permafrost in the ecological subsections of YUCH. Of the fourteen subsections, twelve are believed to contain permafrost.

The remote-sensing technique(s) testing site for Karle and Jorgenson (2004) in located on the right bank of the Yukon River roughly centered at 65º 22' 00" N, 142º 51' 24" W. Please see the DENA section for full details.

Temperatures in a 63 meter borehole located south of YUCH in Eagle, AK were examined by Osterkamp and Romanovsky (1999). Temperature profiles in 1985, 1988, 1991 and 1994 were compared with borehole temperatures from across Alaska. Permafrost temperatures in Eagle were found to not increase during this timeframe, while temperatures along a north-south transect from Old Man, AK to Gulkana, AK and at Healy, AK showed a warming trend.

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