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Advances in Thermokarst Research

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ABSTRACT

The term thermokarst describes the processes and landforms that involve collapse of the land surface as a result of the melting of ground ice. We review the literature that has contributed to our understanding of patterns, processes and feedbacks, and the environmental consequences of thermokarst, focusing on hillslope, thaw lake and wetland processes. Advances in remote sensing techniques, and their application in a broad suite of change detection studies, indicate recent increases in the rates and magnitude of thermokarst including retrogressive thaw slumping, lake expansion and the transformation of frozen peatlands to collapsed wetlands. Field-based studies and modelling have enhanced the knowledge of processes and feedbacks associated with warming permafrost, changes in talik geometry and accelerated thaw slump activity, and thaw lake expansion. Hydrological processes can strongly influence the rates of thaw lake and gully development, and the degradation of frozen peatlands. Field studies and calibrated modelling efforts that investigate the drivers of thermokarst and test conceptual ideas of landscape evolution will be critical to further advance the prediction of landscape and ecosystem change. Thermokarst research provides an important context for studying the environmental implications of permafrost degradation. Hillslope thermokarst can alter the water quality of lakes and streams with implications for aquatic ecosystems. Investigation of the interactions between thermokarst and hydrologic and ecological processes has improved knowledge of the feedbacks that accelerate change or lead to stabilisation in terrestrial and thaw lake environments. Finally, the influence of permafrost thaw on soil carbon dynamics will be an important focus of thermokarst research because of feedbacks with the global climate system. Copyright © Her Majesty the Queen in Right of Canada 2013.

KEY WORDS: thermokarst; climate change; ground ice; ecology; environmental change

INTRODUCTION

Permafrost exerts a fundamental influence on Arctic ecosystems by modifying micro- and macro-scale topography, controlling soil temperature and moisture, and influencing biogeochemical and hydrological processes (French, 2007; Schuur *et al*., 2008; Grosse *et al*., 2011; Heginbottom *et al*., 2012). By providing structural support to the terrain surface, permafrost is also integral to the stability of Arctic ecosystems and infrastructure built on perennially frozen ground. Since the 1970s, permafrost temperatures in the circumpolar Arctic have increased by 2–4 °C in response to accelerated climate warming (Burn and Kokelj, 2009; Romanovsky *et al*., 2010). Permafrost warming and thickening of the active layer are of particular concern because the thawing of ice-rich ground and terrain settlement can modify the landscape and lead to the development of thermokarst terrain (Jorgenson and Osterkamp, 2005). Thawing of ice-rich permafrost can have implications for infrastructure integrity, drive shifts in terrestrial and aquatic ecosystems, and release carbon preserved in frozen ground (Fedorov and Konstantinov, 2008; Tarnocai *et al*., 2009; Callaghan *et al*., 2011; Grosse *et al*., 2011).

Thermokarst refers to the suite of processes by which characteristic landforms result from the thawing of ice-rich permafrost or melting of massive ground ice (Figure 1) (Jorgenson *et al*., 2008). For millennia, thermokarst has played an important role in shaping permafrost landscapes (French, 2007; Murton, 2009). Today, thermokarst is common throughout most permafrost regions including northern Canada (Sannel and Kuhry, 2011), Russia (Veremeeva and Gubin, 2009), Mongolia (Sharkhuu, 1998), China (Wu

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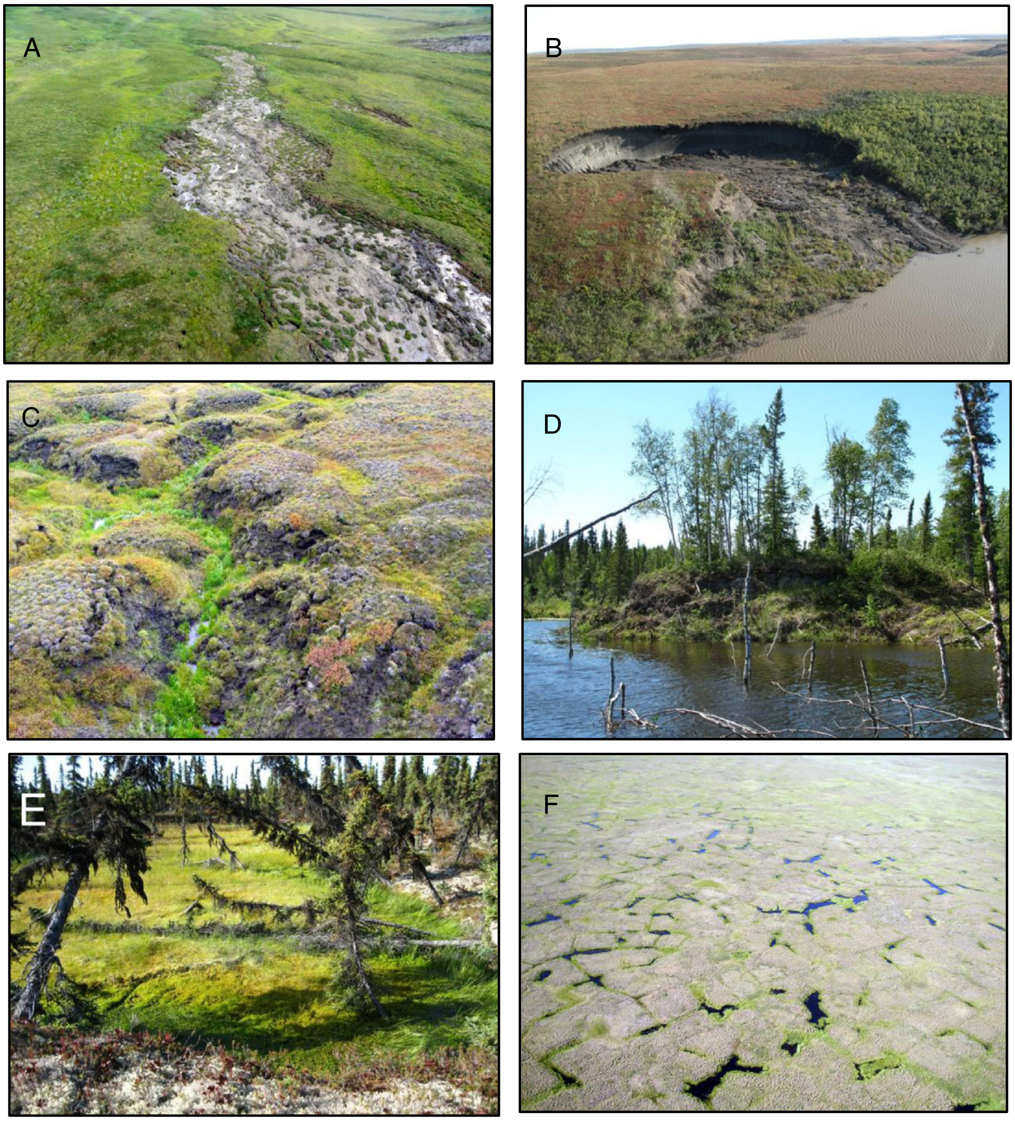

Figure 1 (A) Active-layer detachment slide (~ 20 m wide), western Noatak National Park and Preserve, Alaska; (B) active (~ 250-m diameter; headwall height ~ 10 m) and adjacent stabilised lakeside thaw slumps, Richards Island, Western Arctic, NWT, Canada; (C) thermal erosion gully and the development of high-centred polygons along the Kobuk River, western Alaska (~ 8 m wide); (D) thermokarst lake with submerged trees along an expanding shoreline near Yellowknife, NWT; (E) thermokarst bog with leaning spruce trees, Koyukuk Flats, central Alaska; (F) thermokarst pits and troughs (~ 4 m wide) in polygonal terrain, Beaufort coastal plain, northern Alaska.

et al., 2010), Alaska (Jorgenson *et al*., 2008) and Antarctica (Campbell and Claridge, 2003). Recent climate warming and rising permafrost temperatures have coincided with an increase in the frequency and magnitude of thermokarst (Jorgenson *et al*., 2006; Fedorov and Konstantinov, 2008; Lantz and Kokelj, 2008). The cumulative effects of climate warming and accelerated surface disturbance can act synergistically to increase the impacts of thermokarst on Arctic ecosystems (Lantz *et al*., 2009; Rowland *et al*., 2010) and on carbon cycling (Schuur *et al*., 2008). While ice-rich permafrost is sensitive to climate change and surface disturbance, there are positive and negative feedbacks involving interactions between geomorphology, hydrology, vegetation and ground thermal conditions which can exacerbate or arrest thermokarst processes (Jorgenson and Shur, 2007). Increasingly, multidisciplinary approaches are required to understand the consequences of these changes in northern ecosystems and Earth climate systems (Lantz *et al*., 2009; Schuur *et al*., 2008). Towards this end, there has been renewed international effort to compile data on thermokarst patterns, rates and processes.

This paper reviews recent literature that contributes to our understanding of the processes, feedbacks and environmental consequences of the primary forms of thermokarst. The principal thermokarst types considered include: (1) hillslope processes, including retrogressive thaw slumps, active-layer detachment slides (ALDS) and thermal erosion gullies; (2) thaw lake processes, including lake expansion, drainage and lake basin evolution; and (3) wetland processes, including peatland collapse and the development of bogs and fens. We focus on initiating factors and changing processes, feedbacks, landform evolution and ecosystem impacts. This framework facilitates the summary of our current state of knowledge and the identification of key knowledge gaps.

DIVERSITY OF THERMOKARST TERRAIN

Studies from Arctic, Subarctic and Antarctic regions have identified 22 thermokarst landforms based on their macro- or micro-topography and surface characteristics (Jorgenson *et al*., 2008). This diversity can be attributed to varying topography, surficial materials, ground ice volumes and morphologies, and heat and mass transfer processes. The classification and mapping of thermokarst features are complicated by the diverse ecological responses, the scale, surface and spectral characteristics on aerial photographs and satellite images, variable thaw settlement depths and the wide range of sizes of thermokarst features, ranging from 1 m^2 to thousands of hectares (Jorgenson and Osterkamp, 2005). Some micro-scale thermokarst landforms can occur within larger macro-scale landforms, such as thermokarst troughs and pits within old thermokarst lake basins. An additional complication is that thermokarst landforms undergo temporal changes involving initial and advanced stages of degradation and stabilisation, and dominant physical processes may change as the features evolve. Recovery to original permafrost and ecological conditions is uncommon, and where it occurs it takes a long time.

RESEARCH APPROACHES AND TOOLS

Field techniques for assessing topography, hydrology, thermal regimes and permafrost distribution in relation to thermokarst have benefited from the lower costs of ground-based laser imaging detection and ranging (LIDAR), differential global positioning system (DGPS), and inexpensive temperature and moisture instrumentation. Ground-based LIDAR can provide rapid and detailed topographic data, useful for monitoring the evolution of thaw slumps and areas with ice-wedge degradation. High-resolution DGPS has been used to monitor coastal erosion (Aguirre *et al*., 2008), as well as other thermokarst features. Widely distributed temperature and moisture monitoring with low-cost dataloggers now enables the compilation of ground temperatures from a range of permafrost environments and thermokarst terrain types (Kokelj *et al*., 2009a). Field studies of permafrost dynamics have also benefited from a better recognition of cryostructure and cryofacies analysis that can help interpret permafrost history (French and Shur, 2010). Palaeo-limnological techniques have been utilised to examine the impacts of thermokarst on sedimentation, geochemistry and organic matter in Arctic lakes, and to place contemporary environmental change into a broader historical context (Bouchard *et al*., 2011).

Thermokarst detection and monitoring have benefited from the better availability and declining costs of high-resolution imagery, the improved availability of moderate-resolution imagery for time series analysis and improvements in image processing techniques for mapping thermokarst terrain. High-resolution imagery and aerial photographs are particularly useful for thermokarst mapping because of the wide range of sizes in thermokarst features and their spectral variability (Fortier and Aubé-Maurice, 2008; Sannel and Brown, 2010; Chasmer *et al*., 2010). Numerous studies have analysed thermokarst lake characteristics, changes and drainage through satellite imagery (Figure 2) (Bartsch *et al*., 2008; Labrecque *et al*., 2009; Jones *et al*., 2011; Carroll *et al*., 2011). The high temporal density of satellite imagery can allow rapid processes such as lake drainage to be discriminated from gradual drying or incremental expansion. While the automated mapping and classification of lakes have become routine, improvements in image processing and terrain modelling techniques have expanded the analysis to a broader array of thermokarst features including changes in shoreline morphology, the collapse of frozen peatlands and slope disturbances (Grosse *et al*., 2006; Sheng *et al*., 2008; Balser *et al*., 2009; Sannel and Brown, 2010). Digital terrain models derived from optical stereo, synthetic aperture radar or airborne laser scanning data have been used for investigating permafrost-related mass

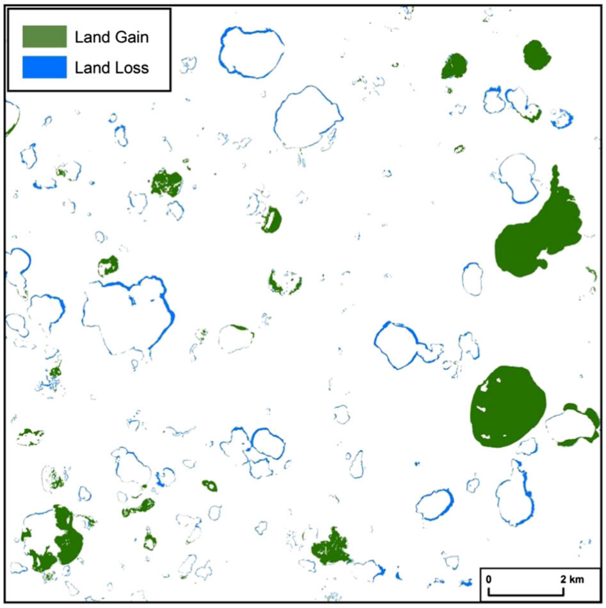

Figure 2 Time series of Landsat imagery provides historical data for assessing changes in shoreline erosion (blue) and lake drainage (green) associated with thermokarst lakes on the northern Seward Peninsula, Alaska (image courtesy of B. Jones, adapted from Jones *et al*., 2011). In this region, lake expansion through shoreline erosion is incremental and continual around features, but the loss of lake area is frequently abrupt, with drainage or partial drainage of entire features.

movements, thaw and heave processes, and hydrological hazards (Kaab, 2008; Short *et al*., 2011). Airborne LIDAR has great potential for monitoring thermokarst, but high costs have limited acquisition to small areas or strips. Figure 3 illustrates the utility of these data in obtaining detailed information on the topography and hydrological connectivity of macro-scale thermokarst features such as thaw lakes, as well as micro-relief associated with thermokarst pits and troughs. The decreasing cost of desktop computer software has improved the use of stereo-photogrammetry, which can be utilised to elucidate geomorphic form and estimate volumes of slope sediment transport resulting from mass-wasting processes (Swanson, 2012). While data acquisition and processing techniques are progressing rapidly, there are notably fewer studies that have focused efforts on obtaining process-oriented field data (e.g. Grom and Pollard, 2008; Kokelj *et al*., 2009a) that can contribute to the development and calibration of physically based models for thermokarst processes (e.g. Plug and West, 2009).

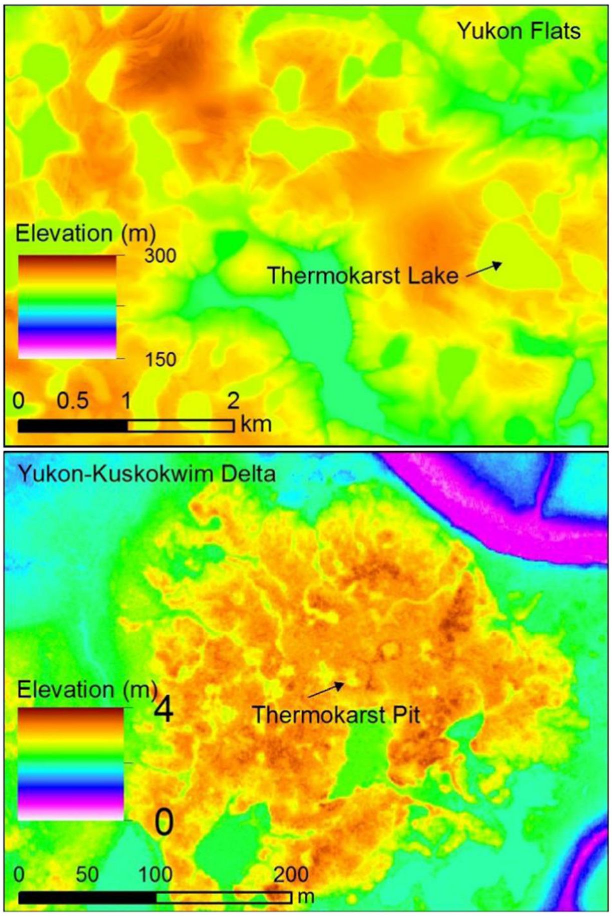

Figure 3 Airborne laser imaging detection and ranging can provide decimetre-to-metre-scale resolution of the topographic relief of thermokarst features. Upper: Digital elevation model of thermokarst lake terrain on extremely ice-rich loess on the Yukon Flats can be used to quantify bank heights, ice volume losses, water surface elevations and hydrologic connectivity. Lower: Thermokarst pits have started to develop on the permafrost plateaus on the Yukon-Kuskokwim Delta, Alaska, and show varying degrees of hydrologic isolation and connectivity.

PATTERNS AND PROCESSES OF MAJOR THERMOKARST LANDFORMS

Active-layer detachment slides (ALDS)

ALDS are rapid mass movements that involve the detachment of thawed active-layer soils and the downslope movement of materials along the base of the active layer. Slides may occur on low-angled slopes, transporting saturated overburden up to several hundred metres downslope (Figure 1A). The characteristics of slides can vary with the geomorphic and ecological setting, but all are typified by a scar area of degraded permafrost, highly disturbed soils along lateral shear zones sometimes accompanied by ridges and a downslope area where earth materials accumulate as an involuted sheet of overridden slope materials or debris-flow deposits (Lewkowicz, 2007). Sliding events often occur following the rapid thaw of the ice-rich transient layer (Lewkowicz, 2007; Lamoureux and Lafrenière, 2009). When ice lenses thaw and water cannot drain away, porewater pressures increase to reduce effective stress at the thaw front (Lewkowicz, 2007). As a result, slides are most common in fine-grained soils with low hydraulic conductivity on slopes underlain by ice-rich permafrost and in association with areas of surface water convergence such as water tracks.

Local-scale disturbance inventories (Ma *et al*., 2006; Lamoureux and Lafrenière, 2009), and regional surveys (Couture and Riopel, 2008; Balser *et al*., 2009; Swanson, 2010) of the distribution of ALDS reveal that they commonly occur in clusters as a result of their association with surficial materials and topography, or as a result of particular initiating events, such as deep active-layer thaw during warm summers, forest or tundra fire, high snowmelt, or extreme precipitation (Gooseff *et al*., 2009; Lamoureux and Lafrenière, 2009). Palaeo-sequences of fluvial deposits suggest periods of intense activity of ALDS during warm, wet conditions in the early Holocene (Mann *et al*., 2010). As the global climate continues to warm, knowledge of the physical factors driving the alteration of disturbance regimes and regional-scale analysis of disturbances will be necessary to assess geohazards and appropriately plan infrastructure development (Ma *et al*., 2006; Blais-Stevens *et al*., 2010).

ALDS can increase slope sediment and solute yields (Lewkowicz and Kokelj, 2002; Lewkowicz, 2007; Lamoureux and Lafrenière, 2009). However, the nature and magnitude of these effects on stream systems are influenced by hydrological connectivity and the physical and geochemical characteristics of near-surface permafrost sediments (Lewis *et al*., 2011; Dugan *et al*., 2012). ALDS can influence the patterns of tundra vegetation communities (Cannone *et al*., 2010). Woods *et al*. (2011) show that ALDS can mobilise carbon sequestered in near-surface permafrost, suggesting that increased disturbance activity could also affect carbon cycling in impacted environments.

Retrogressive Thaw Slumps

Retrogressive thaw slumps represent one of the most dramatic manifestations of permafrost thaw (Figure 1B). These features commonly develop in ice-rich glaciogenic deposits throughout the Canadian Western Arctic (Lantz and Kokelj, 2008; Lacelle *et al*., 2010), the Alaska Range and the Brooks Range and their glaciated foothills (Jorgenson *et al*., 2008; Balser *et al*., 2009), and Siberia (Alexanderson *et al*., 2002). They can also develop along streams and rivers that incise lacustrine deposits (Burn and Lewkowicz, 1990) and in syngenetic permafrost in the yedoma of Siberia and Alaska (Kanevskiy *et al*., 2011). Thaw slumps are initiated through a variety of mechanisms that expose ground ice, including: (1) mechanical erosion by fluvial processes or wave action (Burn and Lewkowicz, 1990; Couture *et al*., 2008); (2) thermally driven subsidence along lakeshores (Kokelj *et al*., 2009a); or (3) mass wasting triggered by extreme thaw or precipitation (Lacelle *et al*., 2010). These trigger mechanisms are impacted by climate change, but the intensity of responses can be expected to vary with the geomorphic setting and local climate. Similar to ALDS, extreme events may also be important in the initiation or rejuvenation of thaw slumps, but large thaw slumps take years to develop making it difficult to establish the linkage between these events and increased slumping.

Numerous processes govern the growth of thaw slumps. Enlargement is caused by summer ablation of ground ice and progressive back-wasting of the ice-rich headwalls (Figure 1B). Heat transfer from radiation and advection from water flowing over the headwall contribute to thawing (Grom and Pollard, 2008). Annual rates of headwall retreat vary from a few metres up to tens of metres per summer (Lantz and Kokelj, 2008; Lantuit and Pollard, 2008; Swanson, 2012) and regression rates generally increase with scarp height (Wang *et al*., 2009). Materials exposed by thawing accumulate as a mud slurry on the slump floor and are transported downslope by mudflow and slopewash (Figure 1B). A slump may grow for decades until exposed ground ice is covered by the accumulation of thawed sediments (Burn and Lewkowicz, 1990; Lantuit and Pollard, 2008). Factors that dictate the growth potential of a thaw slump include the nature and amounts of ground ice, topography, slope, behaviour of the debris flow and accumulation (or lack) of material at the outflow. In subarctic settings, enhanced summer moisture regimes and saturation of the debris flow are thought to accelerate the rates of debris removal (Burn and Lewkowicz, 1990; Lacelle *et al*., 2010).

Slumps are typically polycyclic, in part because they are more likely to develop in areas with ice-rich permafrost and where processes that expose ground ice are most persistent, such as coastal or fluvial settings (Lacelle *et al*., 2010; Lantuit *et al*., 2012). Several internal feedbacks may also re-initiate thaw slumps. Snowmelt, ground ice thaw and rainfall can all contribute to surface runoff and rill development on the slump scar surface, exposing ground ice preserved at the toe of the slope and leading to slump rejuvenation (Lantuit *et al*., 2012). Conversely, the accumulation of debris at the base of disturbed slopes may also protect underlying ground ice from exposure by erosion processes (Lantuit *et al*., 2012). Interactions among snow, vegetation and permafrost warming provide strong feedbacks that contribute to the polycyclic behaviour of lakeside slumps (Kokelj *et al*., 2009a). The concave nature of the thaw slump and the rapid colonisation by tall shrubs promote the trapping of snow in Low Arctic slumps (Figure 1B), which can cause permafrost beneath the slump scar to warm by several degrees. This rapid ground warming contributes to lateral adjustment of the lakeside talik, lake-bottom and shoreline subsidence, the exposure of ground ice and re-initiation of the thaw slump.

Thaw slump activity has accelerated in association with recent climate warming in lake (Lantz and Kokelj, 2008), fluvial (Gooseff *et al*., 2009) and coastal environments (Lantuit and Pollard, 2008). The processes and climate linkages contributing to initiation and the development and perpetuation of larger slumps require further investigation to better anticipate landscape and ecosystem responses to future climate change.

The environmental consequences of thaw slumps are significant. Slumps can thaw the top several metres of ice-rich permafrost and individual disturbances can impact tens of hectares of terrain (Lantuit and Pollard, 2008; Wang *et al*., 2009). Slumps expose thawed materials to weathering and release solutes and carbon previously trapped in the frozen ground. As a result, impacted soils are characterised by elevated soluble ion concentrations and higher pH than the undisturbed tundra (Lantz *et al*., 2009). Runoff over the scars can elevate solute and suspended sediment concentrations in adjacent lakes and streams (Kokelj *et al*., 2009b; Bowden *et al*., 2008). These disturbances can significantly alter the snowpack, ground temperatures, vegetation structure and community composition, as well as the geochemistry of lake-bottom sediments and aquatic food webs (Mesquita *et al*., 2008; Kokelj *et al*., 2009a; Lantz *et al*., 2009).

Thermal Erosion Gullies

Thermal erosion gullies, or thaw gullies, form as a result of heat transfer from channelised flow of surface water into ice-rich soils, causing the active layer to deepen and permafrost to thaw (Figure 1C) (Fortier *et al*., 2007). Typically, these processes are associated with ice-wedge polygon networks because the troughs provide naturally forming flowpaths underlain by relatively pure ice. Gullying in polygonal terrain can lead to rapid lake drainage (McGraw, 2008; Marsh *et al*., 2009) or the development of large gully networks (Fortier *et al*., 2007). These features are typically incised 1–5 m and may extend for hundreds of metres (Godin and Fortier, 2012). Several processes, including thermo-erosional sinkholes, stream capture and tunnel development and collapse, can initiate the gully pattern which may further enlarge via small thaw slumps (Godin and Fortier, 2012). In extremely ice-rich areas, these processes may culminate in high-centred polygons or tall conical mounds (Russian term *baydzherakhi*). Advective heat transfer by running water and tunnel formation and collapse can promote positive feedbacks such as snow accumulation and the capture of other streams which may perpetuate the development of the gully network.

Thermokarst Lakes

Thermokarst lakes and drained lake basins are the most abundant and easily recognisable forms of thermokarst and are widespread in tundra and boreal lowland regions with ice-rich permafrost (Burn, 2002; Grosse *et al*., 2008; Heginbottom *et al*., 2012). Thermokarst lakes have been differentiated on the basis of water depth and regional climate. Lakes deeper than 2 m typically do not freeze to the bottom and therefore maintain a winter habitat for fish and can develop a talik (Burn, 2002; Shur and Osterkamp, 2007; Jorgenson *et al*., 2008). Regional climate is important because lakes in cold regions (mean annual air temperature $< -6\,^{\circ}C$) are likely to maintain permafrost under shallow water, whereas lakes in boreal regions may develop a thaw bulb that extends laterally several metres below the permafrost banks at the surface (Jorgenson *et al*., 2008).

Thermokarst lakes can occupy 20 to 50 per cent of permafrost-affected landscapes (Brown *et al*., 1997; Hinkel *et al*., 2007; Grosse *et al*., 2008). Jones *et al*. (2011) used high-resolution imagery of the northern portion of the Seward Peninsula in Alaska to document that the number of water bodies (> 0.1 ha) increased by 10.7 per cent from 1950–51 to 2006–07, but that the total surface area decreased by 14.9 per cent as a result of the partial drainage of a few large lakes (Figure 2). Lake area, however, can be highly variable over time and closely related to summer precipitation (Plug *et al*., 2008). Vallée and Payette (2007) studied the evolution of mineral palsas and thaw ponds in northern Quebec and found that water levels in the adjacent river system were the most important factor determining pond and palsa dynamics in this environment. Sannel and Kuhry (2011) examined three peatland-dominated areas from sporadic to continuous permafrost zones. At the colder sites, they found little net change in thermokarst lake extent over a 35–50-year period. In the warmer sporadic permafrost environment, significant change included lake drainage and infilling by shore fens, and extensive development of new thermokarst lakes. For small regions, manual interpretation and mapping of water bodies on time series of georectified aerial photographs and recent high-resolution imagery continues to be used (Jorgenson *et al*., 2008), and has proven to be more reliable than semi-automatic remote sensing techniques (Sannel and Brown, 2010).

The development of thermokarst lakes and basins (alases) shows complex patterns related to climate, surficial materials, topography and ground ice (Morgenstern *et al*., 2008). Because of this complexity, many stages of lake development and drainage have been identified that variously include: (1) an initial stage of ice-wedge degradation within flat, high-centred polygons later leading to conical thermokarst mounds (Figure 1C) (Russian term *baydzherakhi*) and pooling of water in troughs (Figure 1F); (2) a shallow depression with distinct margins and a hummocky floor and sides (*dujoda*) without a lake; (3) a broad basin with a flat floor (*tympa*) after complete thawing of the upper permafrost that can further be subdivided into young, mature and old alases that can have a central thermokarst lake; and (4) a basin with a pingo (*khonu*) or a collapsed pingo (Soloviev, 1973). In yedoma deposits of the Lena Delta region, Morgenstern *et al*. (2011) identified: (1) a primary stage of thawing of the ice-rich deposits and lateral expansion; (2) a mature stage with lateral expansion and full talik development; (3) lateral drainage; (4) permafrost development and ice aggradation in the exposed basin floor; (5) coalescence of the thaw lakes, partial drainage and the development of secondary thermokarst lakes in the ice-rich deposits; and (6) pingo development, but not cyclical development of thermokarst lakes. Jorgenson and Shur (2007) found that sediment redistribution by currents causing sandy margins and silty centres was important to ice aggradation after drainage and secondary lake formation. Thermokarst lake formation was extensive during the late Pleistocene-Holocene transition and the Holocene Thermal Maximum (Walter *et al*., 2007; Shilo *et al*., 2007; Veremeeva and Gubin, 2009). Many of the drained lake basins in the northern Yukon were formed during the late Holocene, indicating a period of more frequent drainage or evaporative drying (Lauriol *et al*., 2009). However, since lakes in permafrost regions are formed by many processes, determining whether a lake is caused by thawing permafrost can be problematic (Jorgenson and Shur, 2007).

Numerous factors and processes are involved in thermokarst lake development, including: low albedo and absorption of long-wave radiation; high heat storage capacity of water; convective heat flux from moving water at the lake bottom and shoreline interface; conductive heat transfer through sediments; wave erosion and sediment transport at the collapsing bank; colluvial transport down steep collapsing banks; radiative heating (warming) of ice-rich bluffs occasionally being exposed directly to solar radiation; and thaw settlement beneath the lake (Kokelj *et al*., 2009a; Plug and West, 2009; Grosse *et al*., 2008). Solar heating of water bodies and latent heat effects associated with the phase change of water can account for the significant departure between lake-bottom and air temperatures. This contrast can account for the thawing of permafrost beneath and adjacent to ponds and lakes in Arctic and boreal permafrost regions (Jorgenson *et al*., 2010; Lin *et al*., 2010). In the discontinuous permafrost zone, warm water can cause lateral subsurface thawing under the permafrost margins (Jorgenson *et al*., 2010). Once water depth exceeds the maximum thickness of winter ice cover, temperatures in water below the ice enhance year-round thawing and talik growth (Burn, 2002). Mechanical erosive shoreline processes contribute to lateral lake expansion through: (1) wave action that creates thermo-mechanic erosional niches (Walker, 2008); (2) over-steepening of lake banks resulting in block failures; (3) ice-shove during break-up that removes insulating vegetation and soil; (4) thaw slumps that expose massive ice and cause mudflows (Kokelj *et al*., 2009a); (5) toppling of trees, other vegetation and soil along eroding shorelines (Figure 1D); and (6) the incorporation of polygonal ponds into the lake in areas with abundant ice wedges (Billings and Peterson, 1980). Ground ice content also has a large effect on the rates and morphology of developing thermokarst lakes (West and Plug, 2008). Recent studies have shown that lateral subsurface thawing underneath the shoreline in ice-rich permafrost can lead to accelerated shoreline collapse, thaw slump activity and lake expansion (Kokelj *et al*., 2009a).

Drainage or shrinkage of thermokarst lakes can be affected by the lake water balance (Plug *et al*., 2008; Labrecque *et al*., 2009; Pohl *et al*., 2009) and by external factors, such as melting of the ice-wedge network in the surrounding surface that can create a drainage pathway, headward gully erosion towards a lake, tapping by a river, stream or other lake, or coastal erosion (Hinkel *et al*., 2007; McGraw, 2008; Marsh *et al*., 2009; Arp *et al*., 2011). In the discontinuous permafrost zone, water can drain through open taliks penetrating the thin permafrost layer (Yoshikawa and Hinzman, 2003; Smith *et al*., 2005). Drainage of thermokarst lakes can be extensive in some landscapes. For example, Grosse *et al*. (2005) showed that thermokarst basins cover about 46 per cent of the total land area of the Bykovsky Peninsula, Siberia. However, the current thermokarst lake area is less than half the area that is occupied by thermokarst basins. In many regions, coalesced and overlapping thermokarst basins of differing ages are present (Hinkel *et al*., 2005), indicating the frequent reoccupation of these terrain depressions with new lakes or the renewed growth of remnant lakes. Morgenstern *et al*. (2011) found that developing thermokarst lakes on yedoma uplands occupy only 2.2 per cent of the study area compared to 20.0 per cent occupied by thermokarst basins. Marsh *et al*. (2009) found 41 of the 13 965 lakes that existed in the Canadian Western Arctic in 1950 have since drained and that the rates of lake drainage have decreased slightly during the 1950 to 2000 period. It is important to note that the infilling of lakes by shore fen vegetation can also be a major factor in lake shrinkage in boreal or Low Arctic regions and can complicate change detection because the lake area may be decreasing while the area of thermokarst activity is expanding (Roach *et al*., 2011; Sannel and Kuhry, 2011; Parsekian *et al*., 2011).

Thermokarst lake development has potentially large ecological consequences on local and global scales. Thermokarst lakes and drained basins of varying ages create a diverse ecological landscape that provides a high-value habitat for fish, migratory birds and wildlife. The thawing of ice-rich sediments around thermokarst lakes can have a large effect on sediment and water chemistry (Kokelj *et al*., 2009b; Bouchard *et al*., 2011; Breton *et al*., 2009; Pokrovsky *et al*., 2011). The impacts, however, are related to the nature of the thawing sediments and the proportions of sediment and organic materials that are delivered to the lake. Thermokarst lakes are also extensively used for human purposes as a residential freshwater source in northern communities, as a water source for resource exploration and development, as fishing and hunting grounds and for winter ice road construction (Jones *et al*., 2009).

Thermokarst lakes have been identified as an important source for the atmospheric greenhouse gases carbon dioxide and methane (Walter *et al*., 2006). Drained lake basins provide water-logged soils that are conducive to rapid peat accumulation (Jones *et al*., 2012). The complex dynamics of lake development and drainage indicate that surface stabilisation, permafrost aggradation and ecological succession after lake drainage may limit or modify methane emissions (Zona *et al*., 2010; van Huissteden *et al*., 2011). A recent remote sensing study has shown that, globally, lakes are warming rapidly with ongoing climate change (Schneider and Hook, 2010). In permafrost regions, such warming would not only impact thermokarst lakes as habitats, but in conjunction with warming permafrost, would have profound consequences for their hydrological and morphological dynamics, as well as their life cycle.

Thermokarst Bogs and Fens

Peatlands cover 19 per cent of the northern circumpolar permafrost zones (Tarnocai *et al*., 2009; Jones *et al*., 2010) and are subject to widespread and accelerating rates of thermokarst that can cause extensive development of thermokarst bogs and fens (Figure 1E) (Jorgenson *et al*., 2008; Kuhry, 2008; Thibault and Payette, 2009; Dyke and Sladen, 2010; Bauer and Vitt, 2011; Quinton *et al*., 2011). Bogs are differentiated from fens because of their hydrological, thermal and ecological differences and degradation rates (Jorgenson and Osterkamp, 2005).

Thermokarst bogs are circular depressions formed by the thawing and settlement of ice-rich soils and are widespread on flats throughout the discontinuous permafrost zone (Jorgenson *et al*., 2008; Sannel and Kuhry, 2008). They are associated with ice-rich peat deposits and fine-grained soils on abandoned floodplains, lacustrine plains, lowland loess and gently sloping re-transported deposits. Thaw settlement typically is 1–3 m and bogs slowly degrade laterally at rates of 0.1–0.5 m/yr (Jorgenson *et al*., 2008). Bog vegetation is dominated by ombrotrophic *Sphagnum* and ericaceous shrubs as a result of the isolation of bogs from groundwater movement. The youngest vegetation is found at the collapsing margins.

Thermokarst fens, or collapse-scar fens, are long, linear depressions that occur on flat to gently sloping terrain, where the discharge of groundwater to surface springs can accelerate the collapse of ice-rich lowland deposits (Jorgenson *et al*., 2008). The fens are associated with the degradation of thick-layered ice in silty abandoned floodplains, lowland loess, low areas in till plains and lacustrine basins. They have lateral degradation rates of 0.5–1 m/yr and thaw settlement typically is 1–3 m, and rarely reaches 5 m (Jorgenson *et al*., 2008). Collapse along the margins of fens forms a distinctive 'moat' of slowly flowing water. Fen vegetation is dominated by minerotrophic herbaceous vegetation.

The development of thermokarst bogs and fens has significant ecological consequences because of the associated change in the hydrologic regime (Wright *et al*., 2008; Quinton *et al*., 2009, 2011), the thawing of old frozen soil carbon and sequestration of new carbon (Harden *et al*., 2008; Schuur *et al*., 2008), and the shifts in vegetation from forest to bog and fen communities (Kuhry, 2008). Fire can be an important factor contributing to permafrost degradation and bog development (Myers-Smith *et al*., 2008; Jorgenson *et al*., 2010). Changes in vegetation structure during thermokarst development can cause energy balance changes and positive feedbacks that can enhance degradation (Chasmer *et al*., 2011). Thawing of peatlands and the development of thermokarst bogs and fens can greatly affect land use and the maintenance of infrastructure (Smith *et al*., 2008).

Thermokarst Pits and Troughs

Ice-wedge polygonal networks, abundant in the continuous permafrost zone (Figure 1C, F) (French, 2007), can be sensitive to degradation even under cold climates (Jorgenson *et al*., 2006), and, after thawing, can leave distinctive deposits indicative of past permafrost (French, 2007). Thermokarst troughs and pits are abundant landforms in the flat terrain of the continuous permafrost zone where they form as a result of the degradation of ice wedges. Degradation occurs vertically as the active layer deepens, leading to settlement of 1–2 m, although in areas where water flows through the trough network, settlement may reach 3–4 m (Fortier *et al*., 2007). During the initial stages of ice-wedge degradation, only scattered pits at ice-wedge intersections may be evident. Later, the thawed ice wedges form a polygonal network of water-filled or drained troughs surrounding high-centred polygons (Figure 1C, F). Ice wedges are highly vulnerable to degradation from climate warming, even in the colder continuous permafrost zone, because their tops are commonly just below the active layer (Jorgenson *et al*., 2006; Shur and Osterkamp, 2007). Some terrain can be extremely ice-rich as a result of the large syngenetic ice wedges developed during the late Pleistocene (Kanevskiy *et al*., 2011), but these landscapes tend to develop large conical mounds (*baydzherakhi*) and thaw lakes instead of pits and troughs.

SUMMARY AND CONCLUSIONS

A review of recent literature related to thermokarst reveals an intensification of research by geoscientists and ecologists focused on the investigation of initiating factors and processes, feedbacks, landform evolution and, in particular, ecosystem impacts. These studies are addressing patterns and processes related to a diversity of thermokarst landforms in relation to variations in topography, surficial materials, ground ice volumes and morphologies, and heat and mass transfer processes. Remote sensing and field investigation efforts for assessing topography, hydrology, thermal regimes and permafrost distribution in relation to thermokarst have benefited from the better availability and declining costs of high-resolution imagery, improvements in image processing techniques and software for mapping thermokarst terrain, lower costs of airborne and ground-based LIDAR systems, DGPS, and inexpensive temperature and moisture instrumentation.

The rates and magnitude of development of the predominant types of thermokarst terrain, including thaw slumps, ALDS, thermokarst lakes, thermokarst bogs and fens and thermokarst pits and troughs related to ice-wedge degradation, have accelerated in response to recent climate warming, although site-specific terrain conditions and feedbacks associated with hydrological and ecological processes contribute to high variability. Field-based research in the High Arctic and Subarctic has provided empirical data to support the relations between extreme summer temperatures, precipitation and hillslope mass movements. The integration of field-based approaches and thermal modelling has identified feedbacks between permafrost warming and the initiation and polycyclicity of lakeside thaw slumps. Hillslope thermokarst has the potential to transport large volumes of sediment, solutes and potentially organic carbon to adjacent lakes, streams or the marine environment and to significantly affect both terrestrial and aquatic ecosystems. Progress has been made addressing the complex heat and mass transfer processes associated with the evolution of thaw lakes and identifying a variety of trajectories of thaw lake development as a function of local ground ice and physiographic, geological, hydrological and ecological conditions. Depending on feedbacks between these local conditions, permafrost warming can lead to lake expansion, catastrophic surface drainage, subsurface drainage, or gradual infilling. Frozen boreal peatlands are experiencing extensive transformation to lake, bog or fen, and research has been focusing on influential terrain factors, such as ground ice, surficial materials and hydrology, and the sensitivity of permafrost peatland to fire and anthropogenic disturbance. In Arctic regions, ice wedges are abundant and thermokarst degradation in areas of polygonal terrain has been increasing even in areas of cold permafrost.

Rapid climate warming, especially in the circumpolar Arctic, has increased interest in the processes and consequences of permafrost degradation in tundra and boreal landscapes. In this context, information on the nature, dynamics and distribution of thermokarst and the environmental implications of permafrost thaw are recognised as increasingly important for the planning and management of northern development and the maintenance of resilient northern communities. Studies of thermokarst patterns and processes also provide a critical context for understanding Arctic ecosystem change, the impacts of permafrost loss on carbon dynamics and important feedbacks associated with the global carbon cycle. Research efforts focused on thermokarst processes, including the study of initiating factors, feedbacks and drivers of change, will be critical to advancing physically based modelling efforts and predictions of Arctic landscape and ecosystem change.

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