Arctic permafrost landscapes in transition: towards an integrated Earth system approach

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Abstract: Permafrost science and engineering are of vital importance for northern development and climate adaptation given that buildings, roads, and other infrastructure in many parts of the Arctic depend on permafrost stability. Permafrost also has wide-ranging effects on other features of the Arctic environment including geomorphology, biogeochemical fluxes, tundra plant and animal ecology, and the functioning of lake, river, and coastal marine ecosystems. This review presents an Earth system perspective on permafrost landscapes as an approach towards integration across disciplines. The permafrost system can be described by a three-layer conceptual model, with an upper buffer layer that contains vegetation or infrastructure. Snow and liquid water strongly affect the thermal properties and stability of these layers and their associated interfaces, resulting in critical times and places for accelerated degradation of permafrost and for exchanges of mass and heat with the hydrosphere and atmosphere. Northern permafrost landscapes are now in rapid transition as a result of climate warming and socioeconomic development, which is affecting their ability to provide geosystem and ecosystem services. The Earth system approach provides a framework for identifying linkages, thresholds, and feedbacks among system components, including human systems, and for the development of management strategies to cope with permafrost change.

Keywords: adaptation, Arctic, climate change, cryosphere, permafrost, thermokarst.

Résumé : L’étude et l’ingénierie du pergélisol sont très importantes en matière d’exploitation du Nord et d’adaptation au climat étant donné que les bâtiments, les routes et les autres infrastructures dans plusieurs régions de l’Arctique dépendent de la stabilité du pergélisol. Le pergélisol a aussi des effets à grande échelle sur d’autres caractéristiques de l’environnement arctique y compris sur la géomorphologie, les flux biogéochimiques, l’écologie des plantes et animaux de la toundra et le fonctionnement des écosystèmes lacustres, fluviaux et marins côtiers. Dans le cadre de cette revue, on présente une perspective de système terrestre des paysages de pergélisol en tant qu’approche d’intégration entre les disciplines. Le système de pergélisol peut être décrit au moyen d’un modèle conceptuel à trois couches, avec une couche tampon supérieure où se trouve la végétation ou l’infrastructure. La neige et l’eau liquide influencent fortement sur les propriétés thermiques et la stabilité de ces couches et leurs interfaces associées, donnant lieu à des périodes et endroits critiques sur le plan de la dégradation accélérée du pergélisol et des échanges de masse et de...
chaleur avec l’hydrosphère et l’atmosphère. Les paysages de pergélisol du Nord se trouvent dorénavant en transition rapide du fait du réchauffement climatique et du développement socio-économique, ce qui a des répercussions sur leur capacité de fournir des services écosystémique et géosystémique. L’approche de système terrestre offre un cadre afin de déterminer des liens, des seuils et des rétroactions parmi les composants du système, y compris les systèmes humains, et aux fins de développement de stratégies de gestion en vue de faire face au changement du pergélisol.

Mots-clés : adaptation, Arctique, changement climatique, cryosphère, pergélisol, thermokarst.

Introduction

M. von Buch, in an address which he read to the academy of Berlin in the year 1825, distinctly expressed it as a matter of doubt, whether in a district covered with wood the ground can be in a frozen state at such great a depth as the first excavation at Yakutsk had reached, namely 91 English feet. (Von Baer 1838)

The early reports of “permanently frozen ground” in Siberia were initially greeted with some degree of skepticism, but by the mid-19th century, borehole temperature measurements had been made to great depth and had unequivocally shown that permafrost at Yakutsk extended to well below 100 m. Mining and railway engineers in Siberia contributed to the increasing geophysical knowledge about permafrost, and Russian scientists developed models to predict the southern limit of permafrost in Siberia based on air temperature and snow depth (Anisimov and Reneva 2006). Engineering studies on permafrost in North America began in the 1940s to support wartime road construction in Alaska (Muller 1947), and geophysical research on permafrost rapidly expanded in scope over the subsequent decades. Permafrost research began in China in the 1950s, with a practical emphasis on engineering design, construction, and operation for economic development (Zhang 2005). This long history of permafrost science and engineering gave rise to a detailed level of understanding about thermal dynamics, ground ice features, and periglacial processes (e.g. Mackay 1971; Washburn 1973; Pollard and French 1985; Allard and Seguin 1987; Burn and Lewkowicz 1990; French 2014) and led to engineering design recommendations for construction on permafrost lands (Johnston 1981; Andersland and Ladanyi 2004).

More recently, there has been growing awareness of not only the geophysical and geomorphological importance of permafrost but also of its biogeochemical and ecological significance, including for carbon and other elemental cycling processes, for terrestrial vegetation, wildlife and food webs, and for the functioning of aquatic ecosystems including lakes, rivers, wetlands, and the coastal Arctic Ocean. At a broad systems level, permafrost defines the stability of high-latitude environments, and small climate- or human-induced changes in its properties can induce large-scale shifts in the flow of water, heat, sediments, and solutes, including organic materials. The rapid warming of permafrost soils and accelerated rates of thermokarst (thawing and erosion of ice-rich permafrost) have drawn attention to the impacts of diminishing permafrost stability, not only in natural environments but also for infrastructure in the North such as roads, railway lines, pipelines, aircraft runways, port facilities, buildings, and waste containments. All of these emerging themes have highlighted the need for exchange of permafrost knowledge among disciplines and for an integrated approach towards understanding the implications of changing permafrost conditions across northern lands (Fritz et al. 2015).

This review article outlines a set of integrated perspectives on Arctic permafrost landscapes in transition, with emphasis on an Earth system approach. This approach in the Earth sciences places emphasis on interactions and feedbacks among four compartments of the planetary system: Atmosphere, Hydrosphere, Solid Earth, and Biota (Kump et al. 2010). Human systems and the cryosphere are considered to be subcompartments of the
Biota and Solid Earth, respectively, although both have a strong influence throughout the Earth system. The legacy effect of past climates and events is also an essential element of Earth system science and is highly relevant to permafrost given that most of today’s perennially frozen ground owes its thermal characteristics to earlier periods of sustained cooling and its material characteristics to geological and landscape processes that took place in the past. At Prudhoe Bay, Alaska, for example, thermal modelling indicates that permafrost >600 m in saturated mineral soils would have taken hundreds of thousands of years to form, through several ice ages (Lunardini 1995), while in some subarctic regions, the current permafrost may be a legacy of the Little Ice Age some 300 years ago (Bhiry et al. 2011). Paleoclimate and stratigraphic analysis including via paleolimnological records (e.g. Bouchard et al. 2017) therefore provides valuable historical insights into the current permafrost regime and its likely responses to ongoing climate change.

Our discussions here build on previous system-level views of thermokarst (e.g. Bowden 2010) and carbon mobilization (e.g., Vonk and Gustafsson 2013), and they extend this approach by explicitly incorporating the human dimensions of engineered infrastructure and ecosystem services as well as biogeochemistry and land–water interactions. This approach is related to the “geosystems framework” adopted in engineering studies at the Beaver Creek Road Experimental Site in the Yukon, Canada (Stephani et al. 2014), and is a contribution to the “resilience framework” that recognizes the need to strengthen the local capacity of northern communities for environmental stewardship in the face of rapid and uncertain changes (Chapin et al. 2015). We first review some of the key definitions in permafrost science and then outline steps towards an integrated Earth system approach. These include the development of a three-layer model, recognition of the overarching importance of snow and liquid water for the physical stability of permafrost systems, and a conceptual framework linking the changes in permafrost landscapes to ecosystem services. We conclude this review with some examples of the challenges and integrative management solutions associated with permafrost change. This article introduces topics that were part of the research project “Arctic Development and Adaptation to Permafrost in Transition” (ADAPT) (Vincent et al. 2013), including permafrost-related concepts and questions that are addressed in detail in subsequent review and scientific articles of this special issue of Arctic Science.

Defining permafrost

Extreme cold is a characterizing feature of the North and it results in seasonally and perennially frozen ground. The latter was called “vechnaya merzlota” (“eternal frost” or “ever frozen”) by Sumgin (1927), which he defined as “any Earth material that remains below 0 °C for at least two years.” This practical definition of the term “permafrost” (a word first coined by Siemon W. Muller) was subsequently adopted by the International Permafrost Association, with the modification as “ground that remains at or below 0 °C for at least two consecutive years.” Permafrost landscapes vary in their spatial extent of perennially frozen ground, ranging from continuous (>90% of the land area) to discontinuous (50%–90%), sporadic (10%–50%), and isolated (<10%). Maps based on this classification show the general north–south gradient from continuous to sporadic permafrost that follows the distribution of isotherms (Fig. 1). Such maps, however, are based on limited field data, and permafrost extent is known to be regionally variable as well as changing rapidly in certain regions. Permafrost varies greatly in thickness, extending to a depth of several hundred metres at some locations, and occurs within vast areas of the North including 65% of Russian land territory (Tumel 2002) and 50% of Canadian lands. It is also important in subalpine and alpine regions, including the high-altitude areas that extend over 25% of China.
The composition (geocryology or phase composition: soil, ice, air, unfrozen water, organic content, cryotexture, and cryostructure) of permafrost depends on how it formed originally. There are two modes of formation of permafrost: epigenetic and syngenetic. Epigenetic permafrost owes its existence to the freezing of pre-existing rock or previously deposited surficial deposits that were not originally frozen. Past climate changes play a key role in this process. For example, the major climate shifts and cooling periods of the Quaternary (Glacial, Neo-glacial, Little Ice Age) led to the long term freezing of soils. Syngenetic permafrost formed in sedimentary sequences that accreted under conditions of extreme cold, e.g., yedomas in Russia and Beringia (aeolian and organic), loess sequences, deltas, organic accumulation (peat), alluvium, and colluvium. Carbon stocks are found predominantly in syngenetic permafrost because organic deposition took place and paleosols were trapped in layers as the sediments were accumulating. Most of the carbon stocks in permafrost are therefore legacies of past climates.

Throughout the Arctic, permafrost is overlain by an “active layer,” defined as the upper soil stratum that experiences seasonal freezing and thawing. Changes in the active layer are critically important for the functioning of northern geosystems, ecosystems, and engineered systems because they affect the physical stability of the land, the availability of unfrozen habitat for microbes and plant roots, and the presence and flow paths of liquid water across the landscape. In large part, the depth of the active layer is dictated by climate, itself a function of latitude and altitude. However, local conditions also play a major role,
including snow cover and the nature of the soil or rock substrate, specifically its thermal conductivity. The thickness (Z) of the active layer can be approximated by the Stefan equation:

\[ Z = \sqrt{\frac{2TkL}{T}} \]

where \( T \) is the temperature of the ground surface during thaw, \( k \) is the soil thermal conductivity, \( t \) is the duration of thaw, and \( L \) is the volumetric latent heat of the soil (a function of its water content). This thickness can range from centimetres to several metres, for example up to 3.5 m on Svalbard (Harris et al. 2009). There can be large differences among sites as a result of variations in \( T \) (Fig. 2) or \( k \), including via local differences in the thickness and density of the insulating snow cover (Fig. 3).

An integrative three-layer model

Permafrost lands are described above as a two-layer system that during summer comprises the thawed active layer overlying the frozen permafrost beneath. However, from a broader Earth system perspective, a third layer must be considered: the upper stratum that lies between the Solid Earth active layer and the Atmosphere above. Here, we adopt the term “buffer layer” for this upper stratum based on terminology that has been variously used in the modelling literature (Riseborough et al. 2008). In natural environments, the buffer layer consists of the above-ground vegetation, from polar desert soil crusts to tundra grasses, forbs, and lichens to shrubs and trees farther to the south (Fig. 4). In engineered environments, the buffer layer includes roads, runways, houses, and industrial infrastructure including pads, embankments, buildings, pipelines, waste treatment systems, and mine tailings (Fig. 5). In both cases, this surface buffer layer strongly affects the transfer of heat between the atmosphere and the active layer and thereby affects the stability of the permafrost beneath. This effect is compounded by the accumulation of snow in the buffer layer, which is determined not only by the regional precipitation regime (Fig. 2) but also by the snow-trapping efficiency of above-ground vegetation or engineered structures (Fig. 3) under varying wind and snowdrift conditions. The effects of the buffer layer on liquid water transport and retention may also have a major influence on heat transfer to the lower layers (see below).

In the permafrost engineering literature, the heat transfer properties of the buffer layer are parameterized as \( n \)-factors (Lunardini 1981), which are defined as the ratio of freezing or thawing indices at the ground surface (\( I_{sf}, I_{st} \)) to those in the air (\( I_{af}, I_{at} \)). These indices are calculated as the number of degree-days below and above 0 °C, respectively, and for engineering design purposes are calculated for the three coldest winters and warmest summers during the most recent 30 years of record. The \( n \)-factor is highly dependent on the nature of the buffer layer; for example, the thawing value for this parameter is defined as

\[ n_t = \frac{I_{st}}{I_{at}} \]

and ranges from 0.37 for vegetated land (spruce trees, brush, moss over peat soil) to 1.0 for turf, 2.0 for sand, and gravel and up to 2.3 for asphalt pavement (Andersland and Ladanyi 2004). The low \( n_t \) values for the buffer layer in “a district covered in wood” may be a contributing factor for the long-term persistence of permafrost at Yakutsk that had so puzzled von Buch in 1825 (cited at the beginning of this article), along with the prolonged winters of extreme cold at this site in central Siberia.

The three-layer model as depicted in Figs. 4 and 5 also comprises three dynamic interfaces that have physical, biogeochemical, and biological properties that change on seasonal as well as much longer scales, including with multiyear cycles and shifts in global climate.
For this reason, the interfaces are shown as zones rather than sharp discontinuities. The upper interface between the buffer layer and the overlying atmosphere changes its albedo properties depending on snow cover, and in the longer term with landscape changes, e.g., tundra versus shrubs versus asphalt. These in turn affect the exchange of heat, water, and gases between the landscape and the atmosphere. The heat balance at the interface between the buffer layer and the active layer, i.e., the ground surface, may be strongly influenced by episodes of winter snow melting and accumulation of ice at the base of the snowpack or by the growth of large ice crystals as depth hoar. It can also change over time with shifts in vegetation composition, height, and density. Finally, the third interface, which lies between the active layer and the permafrost, may shift from year to year depending on the extent of active layer thaw. This changing thaw depth can result in ice accumulation, which alters $L$, $k$, and the water conduction properties of this interface and is referred to by Shur et al. (2005) as the “transition zone” (bounded by an upper “transient layer”) that alternates between seasonally frozen ground and permafrost over subdecadal to centennial time scales.

**Snow and water**

The seasonal variations and stability of the three-layer permafrost system are highly dependent upon climate through its effects on ground temperature and duration of thaw ($T$ and $t$ in the Stefan equation above). However, two linked components of the cryosphere–hydrosphere, snow cover and liquid water, strongly modulate this relationship at
a local scale and also affect permafrost stability under infrastructure, thus requiring adaptive engineering solutions. Snow cover is well known for its effects on permafrost warming (Stiegitz et al. 2003) and its maximum depth and duration are projected to change substantially as the Arctic continues to warm, but with large variations among regions (Callaghan et al. 2011). Snow has a direct effect on the thermal dynamics of permafrost, firstly by reflecting solar radiation as a result of its high albedo (>0.8 for fresh snow versus ≤0.2 for rock and bare ground) and secondly by insulating the ground through its low thermal diffusivity (3.6 × 10⁻³ for uncompacted snow versus 1.1 × 10⁻² for freshwater ice and 2.0 × 10⁻² for dry sand, all in units of cm² s⁻¹). The freezing $n$-factor ($n_f = I_{sf}/I_{af}$) is inversely related to snow depth and can show large variations as a result of human modification of the landscape; for example, a study of the Barrow region, Alaska, showed that this winter $n_f$ had its lowest values in urban areas and also its largest variability in these areas, likely as a result of snow drift and accumulation patterns associated with buildings, plowed roads, and snow fences (Hinkel et al. 2008).

Water (and the transformation to liquid from solid ice and snow) plays a major role by driving heat, sediment, carbon, and microbial transport in permafrost systems. Work over the last few decades has typically placed emphasis on sensible and radiative heat transfer from the atmosphere to soils, but observations on eroding permafrost landscapes and failing infrastructure (e.g., northern airstrips, roads, and building foundations) suggest...
that liquid water and its advective heat transport effects have been underestimated and will require closer attention in the future to understand and manage the fast-changing cryosphere.

The thermo-erosive effects of liquid water are well known from continuous permafrost landscapes, with the melting of ground ice and downstream transport of water, sediments, solutes, and heat. One such example is on Bylot Island, Nunavut, where the genesis and evolution of thermo-erosion gullies have been studied (Godin et al. 2014). In one such area, the flow regime shifted from multiple water tracks to highly channelized flow over the course of a few decades and mobilized large quantities of sediments from the eroding permafrost. This gullying process lowered the residence time of water by increasing the hydrological connectivity of the valley and thereby shifted the wetlands to a drier regime.

The effects of liquid water in transporting heat and kinetic energy mean that the one-dimensional schematic models shown in Figs. 4 and 5 need to be viewed as simplified components of the larger, hydrologically connected, three-dimensional landscape. When permafrost starts to degrade, flowing water will exert major positive feedback effects such as channel erosion, gullying, and thermokarst lake drainage. These impacts of flowing water on transport, accelerated thaw, and spatial patterning will require much greater attention in the future by the permafrost research community.

Fig. 4. The three-layer model applied to natural landscapes. As illustrated here, the buffer layer varies greatly in its geometry (thickness), albedo, and other physical properties, both within and between landscapes, and as a function of vegetation type and season. The arrows indicate exchanges of heat, water, and gases and the white bands indicate interface zones. Upper left: Ward Hunt Island, Nunavut; upper right: Daring Lake, Northwest Territories; lower left: BGR valley, Nunavik; lower right: Umiujaq region, Nunavik.
Studying the processes that couple environmental change to geo-ecosystem state and rate variables (Fig. 6) requires special attention to the critical places and times of rapid changes in water, snow, and permafrost characteristics that have strong effects on the natural or engineered landscape. The environmental change may be the result of human disturbance of permafrost landscapes through local and global effects or the result of natural disturbances (also prone to human modification) such as fire, floods, rain-on-snow, animal activities, erosion, and other processes that modify the buffer zone. In the ecosystem literature, critical places and times have been referred to as “biogeochemical hotspots and hot moments” (McClain et al. 2003). Geo-ecosystem services include wildlife habitat availability, biodiversity, plant and animal production for harvesting, water quality and supply, carbon and nitrogen cycling, greenhouse gas consumption, carbon sequestration, flood and erosion control, and ground stability for infrastructure. Analysis of these Earth system service effects is necessary to inform adaptation and development strategies, which themselves influence snow accumulation, water transport, and permafrost stability (Fig. 6), in order to counteract the impact of climate change on permafrost.

The “critical times and places” perspective is relevant to understanding landscape dynamics and wildlife ecology in the changing northern climate. For example, many wave-exposed locations along coastal environments in the North are prone to permafrost thawing,
with implications for global carbon fluxes, local marine food webs, and human settlements at certain places (Fritz et al. 2017). Retrogressive thaw slumps are critical places of landscape perturbation where soil and vegetation are displaced downslope; studies in the Canadian High Arctic show that these are localized sites of reduced vegetation coverage, increased wet soil conditions, and altered CO₂ exchange with the atmosphere (Cassidy et al. 2017). Abrupt landscape changes can also affect wildlife habitats by altering critical sites such as lakes and ponds for aquatic animals, including water fowl, and by destroying permanent structures used for reproduction such as fox dens and bird nesting sites (Berteaux et al. 2017). One example of the latter from the High Arctic is the loss of cliff-nesting sites for rough-legged hawks (*Buteo lagopus*) caused by mass movements of steep permafrost terrain as a result of heavy rainfall events and warm temperatures during summer (Beardsell et al. 2017). These rapid ecosystem changes also have impacts on the well-being of northern residents. For example, catastrophic lake drainage and evaporative losses have been observed with great concern in the permafrost wetland area of Old Crow Flats in the Yukon, Canada, which is of ecological and cultural significance to the Vuntut Gwitchin, the First Nation “people of the lakes” who have lived in this place for millennia and now face disrupted landscape conditions (Tondu et al. 2017).

Consideration of critical times and places is also highly relevant to identifying the vulnerability of northern infrastructure to ongoing permafrost change. In Russia, most of the northern population lives in multistorey buildings within cities that were developed during the Soviet era of economic expansion in the North to support extractive industries, including coal (such as Vorkuta), gas (Nadym, Salehard, Novyy Urengo), oil (Surgut, Nefteyugansk), and mineral ores (Norilsk), and to service the Northern Sea Route and river transportation (Igarka, Dudinka, Dickson, Pevek). The application of climate models to these regions has shown that the load-bearing capacity of permafrost will decline substantially over the decades ahead and that the most vulnerable cities will be those at the southern margin of discontinuous permafrost (Shiklomanov et al. 2017). This study also draws attention to how local circumstances can hasten the collapse of urban infrastructure,
for example, through the leakage of poorly maintained water and sewage systems, or the removal and redistribution of snow, that accelerates permafrost thawing and subsidence. As another example of a critical place for infrastructure vulnerability, O’Neill and Burn (2017) have shown via observations and modelling that that the deep snow that accumulates at the toe of road embankments on permafrost landscapes results in greater thaw depths than in undisturbed tundra and that active removal or compaction of this snow could provide a way to mitigate against permafrost degradation and road collapse.

**Spatial variations and connectivity**

Permafrost lands vary greatly in horizontal space, and the properties of each of the three layers and their interfaces can also change over short length scales. Many northern landscapes are only partially underlain by permafrost, and permafrost units of the type depicted in Figs. 4 and 5 are interspersed with nonpermafrost units including lakes, bogs, rivers, and unfrozen ground. These nonpermafrost units may also be conceptualized as three-layer systems, with a surface layer of snow and, if on land, plants and infrastructure. This buffer layer overlies a seasonally frozen layer (lake ice, river ice, or seasonally frozen soil), which in turn overlies an unfrozen layer: liquid water in the case of lakes and rivers or perennially unfrozen soil in the case of land. Observations of shallow thermokarst lakes in Alaska that were previously underlain by permafrost suggest that many are crossing a thermal threshold as a result of warmer winters, increased snow cover, and thinner ice; the result is prolonged conditions of liquid water that warm and may completely thaw the permafrost beneath (Arp et al. 2016; see also Langer et al. 2016).

One example of the mosaic of permafrost and nonpermafrost units is in subarctic peatlands, as shown in Fig. 7, where there is a transition from dry, wind-swept palsas (raised mounds containing permafrost) to lowland bogs containing lakes, ponds, and water-saturated soils without a permafrost underlayer. There is a strong lateral coupling of these adjacent landscape units, with water flow and eroding, carbon-rich permafrost enriching the lakes and ponds and stimulating bacterial decomposition activity. The production and net efflux of greenhouse gases from these thermokarst waterbodies reaches up to 240 mmol CO$_2$ m$^{-2}$ day$^{-1}$ and 10 mmol CH$_4$ m$^{-2}$ day$^{-1}$, which greatly exceeds the fluxes from thermokarst lakes in less carbon-rich, yedoma landscapes (Matveev et al. 2016).

The permafrost subsystem is intimately linked to the atmosphere by heat and gas exchanges and to the hydrosphere, ultimately via river flow to the ocean. Atmospheric carbon exchange may vary over short length scales, depending on the landscape type as in Fig. 7, and as a function of vegetation type. For example, on the open tundra at Daring Lake, Northwest Territories, Canada, photosynthetic CO$_2$ uptake rates varied from 50 to 74 g C m$^{-2}$ for relatively dry mixed tundra (for the period 15 May to 31 August) to 63–111 g C m$^{-2}$ in a wet fen environment (Grant et al. 2015). Large quantities of particulate and organic carbon released by degrading permafrost are transported by streams and rivers to coastal seas, where they may be sequestered by sedimentation and burial or converted to CO$_2$ by bacterial and photochemical processes (Vonk et al. 2015). Freshwater ecosystems may also sequester carbon by burial in thermokarst lakes that become completely filled in with sediment (Walter Anthony et al. 2014) and by incorporation into plant biomass such as peatland mosses that are subsequently resistant to decomposition.

**Permafrost lands in transition**

Public interest in Arctic climate change has been especially focused upon sea ice retreat and the associated effects on marine biota. Yet the changes being observed on permafrost lands in the Arctic are equally pronounced, with impacts on plant, animal, and microbial populations. Humans have lived in this region for millennia, and northern settlements
now face unprecedented change though the combined effects of climate warming and economic development. Additionally, the potential release of globally significant amounts carbon via Arctic soil processes (Schuur et al. 2008, 2015), lake metabolism (Matveev et al. 2016; Wik et al. 2016), and coastal erosion (Fritz et al. 2017) have focused increased attention on the stability of northern permafrost landscapes.

Borehole measurements of temperature profiles in Arctic permafrost lands are a vitally important record of environmental change and are increasingly available though open-access local and national data archives (e.g. Allard et al. 2015) and through the global
data base Global Terrestrial Network for Permafrost (GTN-P) (Biskaborn et al. 2015). These measurements have underscored the large spatial variablity in temperature regimes and in the magnitude of recent change. In North America, borehole measurements show that permafrost has been warming in the western Arctic since the 1970s and in parts of eastern Canada since the early 1990s; especially strong warming was observed between 1985 and 2000 in the region north of the Brooks Range, Alaska, with an increase of temperature at 20 m depth by 1.5 to 2.5 °C (Smith et al. 2010). Similarly in Russia, recent permafrost warming is apparent in most borehole records but also with large variations among sites; warming over two to three decades was mostly within the range 0.5 to 2 °C at the depth of zero annual amplitude (Romanovsky et al. 2010).

As a consequence of this pronounced warming, changes are taking place in the geomorphology of the northern landscape and are being amplified by the effects of snow and liquid water. Climate-related changes have been observed in upland permafrost thermokarst that result in the downstream export of sediments and solutes (Abbott et al. 2015), and large changes are noted in the production and loss of thermokarst lakes throughout the Arctic. These latter waterbodies lie in depressions that are formed by thawing and subsidence of ice-rich permafrost, and they occur in great abundance across the northern landscape (Pienitz et al. 2008). An isotopic analysis of the precipitation–evaporation balance of thermokarst lakes at several locations across North America indicates large region-specific variations in their hydrological regime (MacDonald et al. 2017). At some locations, these lakes are evaporating to dryness (e.g., part of the Old Crow Flats region and on the western Hudson Bay lowlands (MacDonald et al. 2017)) or draining through erosion to rivers, sometimes via catastrophic, complete drainage events (Jones and Arp 2015), while in other locations, there is an expansion of thermokarst lake areas and numbers, e.g. Prudhoe Bay, Alaska (see below), and eastern Hudson Bay (Bhiry et al. 2011; MacDonald et al. 2017).

A related effect is in the degradation of ice wedges, which have formed over centuries to millennia in many parts of the circumpolar North. Recent field and remote sensing observations in the Arctic have shown that melting at the tops of ice wedges and associated ground subsidence is now widespread and that this is leading to a change in hydrological patterns, an overall draining of some landscapes, and a change in vegetation (Liljedahl et al. 2016). These changes are especially sensitive to extreme warming events, which may increase in magnitude and frequency with ongoing climate change.

Changes in snowfall patterns are likely to have wide-ranging effects on the ecology of northern biota, including animal populations (see Berteaux et al. 2017), as well as on water supply, landscape stability, and infrastructure. Climate projections indicate a major decrease in snowfall by the end of this century, which will affect the buffer layer and its insolation properties. Total precipitation in the Arctic is expected to increase as rain rather than snow, which is likely to have widespread consequences (Bintanja and Andry 2017). Modelling analysis of winter rain at northern latitudes indicates that this will accelerate permafrost thawing by advecting latent heat to the bottom of the snowpack (Westermann et al. 2011). Extreme precipitation events are also expected to rise in frequency with increasing temperatures (Wang et al. 2017), and the resultant peaks in water flow are likely to accelerate permafrost thawing and erosion.

One of the broader concerns about northern warming is the implication for soil decomposition and carbon emissions to the atmosphere (Schuur et al. 2008), given that the permafrost compartment of the Earth system represents a globally significant carbon store (Schuur et al. 2015). A recent spatial extrapolation concluded that the Arctic permafrost region contains 1300 Pg of organic carbon, of which 800 Pg is perennially frozen (Hugelius et al. 2014). The latter figure is lower than earlier estimates but is of the same order as the amount of carbon in the atmosphere (850 Pg at 400 ppmv CO₂). As illustrated by analyses at
the ADAPT sites (Fig. 8), the organic carbon content of northern soils and associated properties such as C:N ratios vary by orders of magnitude. This variability occurs both within and among locations across the Arctic (see Jones et al. (2009) for soil maps), which underscores the need for improved data collection to constrain the circumpolar estimates. The lability of permafrost carbon is also highly variable and is the subject of intense research. Calculations of permafrost carbon mobilization in a warming climate under the Intergovernmental Panel on Climate Change (IPCC) representative concentration pathway (RCP) 8.5 scenario indicated that 120 ± 85 Gt of carbon could be released from thawing permafrost by 2100, increasing global temperatures by 0.29 °C, but with large amounts of uncertainty (Schaefer et al. 2014). Further analysis concluded that a sudden release of carbon from permafrost as a pulse of greenhouse gases, with catastrophic effects on global climate, seems unlikely (Schuur et al. 2015). Instead, these carbon stores will be gradually mobilized and released over decades to centuries, with ongoing incremental costs to society. However, some of the highest rates of methane emission occur under conditions of abrupt thaw that is accelerated by liquid water pooling and transport, and the relative importance of abrupt versus gradual thaw across the landscape is a major source of uncertainty for assessing permafrost carbon–climate feedbacks (Schuur et al. 2015). The effects of permafrost thaw and carbon release to the atmosphere may be partially offset by increased terrestrial vegetation and photosynthetic CO2 fixation. Syntheses of plot-scale studies show an increase in plant cover throughout the Arctic (Elmendorf et al. 2012) and satellite observations show evidence of greening of high northern latitudes that is closely correlated with climate change, indicating increased carbon storage in plant biomass (Zhu et al. 2016).

Permafrost degradation is also leading to increased mobilization and transport of materials via rivers to the Arctic Ocean. Analysis of the Mackenzie River system has shown that over the last few decades, there has been a 39% increase in dissolved organic carbon (DOC).
 flux at the river mouth, accompanied by a 12% increase in alkalinity flux (Tank et al. 2016). This large change in land-to-ocean transport of organic and inorganic carbon is likely due to degrading permafrost in the northern regions of the river basin, with the alkalinity effects attributed to weathering of sulfides that were previously locked in frozen glacial till. These processes are likely to increase the flux of carbon from the thawing permafrost layer to the atmosphere, since much of the DOC may be mineralized to CO₂ in the river, estuary, and coastal Arctic Ocean by photodegradation and bacterial decomposition (Vallières et al. 2008; Cory et al. 2014), and the sulfide weathering reactions also result in the production of CO₂ (Tank et al. 2016). DOC is additionally released from ice-rich permafrost coasts that are eroding into the Arctic Ocean; however, these fluxes appear to be low relative to riverine inputs and much lower than the vast quantities of particulate organic carbon that are transferred from the land to sea due to coastal permafrost erosion (Tanski et al. 2016).

For northern municipal and industrial developments, landscape change is the result of both climate warming effects and the impacts of engineered structures (Fig. 5). A striking example is the large-scale oil industry development at Prudhoe Bay, Alaska (Raynolds et al. 2014). For the period 1970 to 2012, there was a marked increase in mean annual air temperature and thawing degree-months (by approximately 5 degree-months), which was accompanied by a deepening of the active layer and an increase in permafrost temperatures at 20 m depth. Detailed spatial analysis of nearby landscapes that were unaffected by infrastructure showed that lakeshore erosion increased more than fourfold over the period 1983 to 2010, while the area of thermokarst increased 1.8-fold between 1990 and 2010. Much greater changes were observed in the region of infrastructure development. Extensive flooding, covering up to 20% of certain areas, now occurs because of damming of runoff during the spring melt season by pipelines and roads. Additionally, thermokarst developed rapidly soon after roads were constructed and consistently expanded over the 42 year period of records. In addition to retention of liquid water that accelerates heat transfer and thermo-erosion, three other effects of roads were identified on active layer deepening and thermokarst: the killing of roadside vegetation by dust, thereby destabilizing the ground, the effect of dust in reducing the albedo of the snow buffer layer next to roads, resulting in accelerating snow melt and flooding, and accumulation of snowdrifts by the road embankments, resulting in warmer winter soil temperatures.

**Adaptation to changing permafrost**

Human forcing of the permafrost system, both via the global climate system and through local engineering activities, now poses an immense set of challenges for maintaining the integrity of northern landscapes, ecosystems, and infrastructure. As described above, snow and liquid water have wide-ranging effects, and the local control of these effects provides a basis for adaptive engineering strategies. In this way, iterative knowledge exchange of new research findings, management protocols, and local experience can offset or help reduce the impacts of climate warming and economic development (Fig. 9). Knowledge about the physical properties of the buffer layer is providing insights into how northern landscapes may change in the future, including via shifts in slope stability and vegetation. Ground ice in the permafrost layer, in ice wedges, and in the ice-rich zone at the interface between the active layer and permafrost has long been recognized by permafrost scientists and engineers for its vulnerability to melting, resultant loss of soil volume, and effects on land subsidence. The thermo-erosion effects of liquid water from these sources as well as from snow and rain also require attention to assess the stability of landscapes and infrastructure in a warming climate.
Fig. 9. Adaptation to permafrost landscapes in transition in response to the changing global environment and the local effects of socioeconomic development. Changes in permafrost landscapes driven by climate change have cumulative impacts (boxes 1 to 4). Similarly, development and construction projects require adaptation solutions to minimize their impacts on the built environment and to reduce positive feedbacks of infrastructure on the environment and services (boxes 5 to 8). Engagement of scientists is needed with stakeholders at multiple levels, along with cooperation between public (9) and private (10) sectors to achieve sustainable development in the changing Arctic.
Finally, the lithology, geomorphology, and Quaternary history of the landscape and its spatial variations need to be considered, with careful mapping and characterization of the three-layer permafrost system in order to identify zones of high and low stability (critical places) for adaptive planning.

One example of snow management is the design of road embankments to minimize the accumulation of snowpack and thereby reduce the insulating effects of the buffer layer. Analyses of the freezing $n$-factor for snow in engineering studies of transport infrastructure have shown a negative logarithmic relationship with snow depth, with the initial 40 cm of snow accumulation having the greatest effect on freezing reduction (Lanouette et al. 2015). Observations and modelling have shown that a gentle slope (around 1:7) is optimal for favouring the displacement of blowing snow away from roads and to maximize the cooling of the underlying permafrost. Steeper slopes can result in an economy of road-building material, but they are more prone to the buildup of snowdrifts, with the resultant warming of the active layer and permafrost that in turn can result in subsidence and structural failure. An analysis of runways and their access roads in Nunavik has shown that steep slopes are associated with permafrost degradation as a result of both snow and water accumulation at the toe of the embankment (a critical place as depicted in Fig. 6), and gentler slopes combined with improved drainage are now being adopted to help protect this infrastructure from permafrost thawing (L’Hérault et al. 2015).

Snow fences are installed along some northern transport routes to reduce the effects of blowing snow on visibility for driving and these become critical places for snow accumulation and thermal impacts. A study of a snow fence installed for 35 years along the Peel Plateau of the Dempster Highway confirmed that snow cover, ground temperatures, and late-summer thaw depth and moisture content were all higher along the fence than in the nearby ground. (O’Neill and Burn 2016). The ground had subsided by about 50 cm and a talik (ground that persists unfrozen throughout the year) had developed under the fence. Simulations indicated that the thaw depth had increased from 0.5 to 3 m and that permafrost degradation would continue for many decades, even under the current air temperature regime. Similarly at Barrow, Alaska, studies of a snow fence showed that the thicker snowdrift accumulation resulted in soil temperatures that were 2 to 14 °C warmer than at a control site in winter and that thermokarst was caused not only by this increased warmth but also by the ponding of snow meltwater (Hinkel and Hurd 2006). In some circumstances, snow fences have been employed to intentionally increase snow accumulation and meltwater production. Lake water supply for northern communities can be problematical in winter because of freezeup followed by rapid drawdown and evaporation in summer. An experimental use of a snow fence in Alaska, south of Prudhoe Bay, showed that the resultant snowdrift resulted in an increase of 21% to 29% of lake water volume and prevented the lake from drying out in summer (Stuefer and Kane 2016).

The shift from a snow- to rain-dominated Arctic (Bintanja and Andry 2017) will have major effects on landscapes and infrastructure and will require close attention in future climate projections and regional impact assessments. Rainfall is likely to completely change the timing and pathways of water flow in High Arctic watersheds that are presently dominated by subsurface water tracks fed by long-lasting snow banks (e.g., Paquette et al. 2017). Hill slopes that become saturated in water can suddenly collapse as a result of active layer detachment slides, a thermokarst process that has been identified as a major driver of landscape change in ice-rich permafrost environments (e.g., Lewkowicz 1987).

Increasing summer rainfall that thaws and destabilizes the frozen slopes leads to an increasing number and expansion of retrogressive thaw slumps. These are large thermokarst features that affect ice-rich permafrost and deliver huge amounts of
thawed sediments in mudflows. For example, a study in the Peel Plateau of Northwest Territories region has shown a recent increase in those “megaslumps” that can each transport up to $10^6$ m$^3$ of previously frozen materials. The hydrological connectivity of this permafrost system means that these are likely to have an impact on the water quality and ecosystem processes in downstream rivers, lakes, and the coastal ocean (Kokelj et al. 2015).

Surface water accumulation is known to have a deleterious impact on the thermal regime and stability of road embankments, and such effects are being examined experimentally on a section of the Alaska Highway at Beaver Creek, Yukon, Alaska (Stephani et al. 2014). The observations have shown that poorly drained areas delay the freeze-back of the active layer during winter and also favour ground water flow under the road that can potentially cause further permafrost degradation and collapse (De Grandpré et al. 2012). Drainage and culvert design to channel liquid water and prevent ponding will therefore be increasingly important for road protection over permafrost lands. In a related study at the test section of road at Beaver Creek, the effects of pavement albedo were evaluated by observations and modelling and culminated in a set of engineering design charts (Dumais and Doré 2016).

Close attention to spatial variations and history of the three-layer permafrost system is essential for adaptive planning of new infrastructure in the North. For example, design of the 140 km road across permafrost landscapes from Inuvik to the coastal village of Tuktoyaktuk in Northwest Territories, Canada, involved extensive surveys to map regions of active ice wedge polygons, which are not always visible from aerial photographs. This information was used to identify areas to be avoided, or if that was not possible, to assess the risk of thermal erosion and to design the embankment for protection of the shoulder of the road from thermokarst pond formation and collapse. The ground surveys (including permafrost drilling with recovery) also confirmed the presence of an ice-rich zone beneath the active layer, finally assumed to be horizontally continuous for the purposes of road design (calculation of gravel embankment thickness) to maintain the frozen ground conditions and avoid massive subsidence (Hayley 2015).

An example of the adaptive approach to permafrost landscape management is the municipal planning strategy for the Inuit village of Salluit in northern Quebec (Nunavik, Canada). This area has experienced rapid warming over the last two decades and evidence of permafrost subsidence created great concern, even to the extent of discussing relocation of the entire village of 1400 people. Permafrost system analysis at this site involved an integrated, multitechnique, multidisciplinary approach, from geophysical surveys to community consultation and land use mapping (Allard et al. 2012). Firstly, the Quaternary geology of the area was mapped via aerial photography and high-resolution satellite remote sensing, and this was complemented with field surveys including soil pits and more than 100 drill holes with recovery. Local surveys were made using ground-penetrating radar and electric resistivity, and special attention was given to mapping surficial deposits; for example, till, a mixture of boulders, gravel, sand, and silt, is common throughout this region and is often so rich in ice that thawing can result in substantial ground subsidence. Geomorphological features were also mapped as indicators of ground ice. The ice content of frozen permafrost cores was determined by tomodensitometric scans (CT-scans) (Calmels and Allard 2004), and additional laboratory analyses were performed of grain size and geotechnical properties. For analysis and municipal planning at Salluit, the information from all of these sources was integrated in a geographic information system application, with the information layers showing the spatial distribution in and around the town of elevation, drainage, periglacial features, and infrastructure (Fig. 10). Numerical modelling combined with in situ records of borehole temperatures was then used to project future changes in
permafrost landscape stability. These spatial data and projections were presented and discussed with local residents, elected officials, and planning staff and resulted in a risk management map (Fig. 10A), which in turn was used to help produce a land use plan (Fig. 10B), to identify regions where buildings can be safely constructed and with guidelines for the most suitable foundation types for each category of terrain.

**Fig 10.** Adaptive permafrost landscape mapping at Salluit, Nunavik, Canada. (A) Risk management (geohazard) map based on surveys of surficial deposits and their ice content; (B) Land use plan based on the risk management map. Modified from Allard et al. (2012).

1. **Bedrock and superficial deposits without or with little ice content**
   - a) Bedrock with sparse thin patches of sand, appropriate for all types of northern foundation
   - b) Layered sand and gravel deposits, pore ice and occasional ice lenses. Adjustable foundations recommended (e.g. post and piles)

2. **Ice-rich permafrost in superficial deposits**
   - a) Thin cover of sand, gravel and till over bedrock, ice content varying from 15 to 70%, thaw settlement restricted to superficial cover. Advanced techniques of terrain preparation recommended (e.g. removal) for slab-on-grade foundations
   - b) Thick cover of sand, gravel and till over bedrock, ice content varying from 15 to 70%, subject to thaw settlement. Adjustable foundation installed into deep drill-hole recommended and advanced engineering solutions (e.g. thermosyphons) may sometimes be required.
   - c) Thick cover Quaternary sediments, poorly drained with peat cover, ice-rich and presence of massive ground ice (e.g. ice-wedges), avoid for construction.
   - d) Marine sediment (fine-grained) subject to differential thaw settlement and active layer failures, ice content from 30 to 100%, adjustable foundation recommended, and advanced techniques of terrain preparation recommended (e.g. removal) for slab-on-grade foundations, engineering solutions (e.g. thermosyphons) may sometimes be required.
Geohazard mapping to adapt to permafrost landscape change is also being applied at a continental scale. In Russia, projections of active layer thickness and data from maps of permafrost and ground ice conditions have been used to calculate a hazard index, defined as

\[ I_G = \Delta Z_{al} V_{ice} \]

where \( \Delta Z_{al} \) is the projected change in active layer thickness based on a model driven by estimates of mean monthly averaged air temperatures and precipitation and \( V_{ice} \) is the present-day volumetric content of ice (Anisimov and Reneva 2006). A predictive hazard map was then prepared using a median climate warming scenario for 2050, and the country was partitioned into areas of low, moderate, and high potential hazard to structures built on permafrost. The results show that vast areas of Russia lie in the high potential hazard zone, with likely impacts on roads, pipelines, and rail tracks. In western Siberia, already several thousand ruptures and related incidents are reported each year caused by mechanical damage to oil and gas pipelines as a result of permafrost thawing and subsidence under their foundations (N.N. Nikolaev 1999, cited in Anisimov and Reneva 2006). Such effects can be mitigated by the installation of heat pipes (thermosiphons) to maintain frozen ground conditions as well as diversion of ground water (e.g., as implemented for the Trans-Alaska Pipeline, USA (Mobley et al. 1998)). The rapid development of extensive thermo-erosion gullies has also created problems during construction at various sites in Russia (Tumel 2002), underscoring the need to manage liquid water flow.

For all of these landscape and infrastructure examples, advances in technology for spatial and temporal monitoring are providing improved ways to assess the critical times and places of permafrost change that affect geo-ecosystem services (Fig. 6). At the largest scale, satellite remote sensing provides synoptic data from throughout the entire circumpolar North, for example, of land surface temperature (Hachem et al. 2012) and vegetation (Zhu et al. 2016). New satellites are being launched each year that provide additional capabilities in terms of spatial resolution, revisit cycle, and spectrum and mode of imaging (Liu 2015). For example, satellite-based Synthetic Aperture Radar Interferometry has recently been shown to have sufficient resolution to map surface deformations, particularly annual heave and settlement due to active layer freeze-back and thawing and long-term subsidence; this high-resolution (3 to 10 cm vertical and ~1 m spatial) information is an indicator of potentially ice-rich permafrost that poses risks to roads and runways (Eppler et al. 2015). At a broader regional level, analysis of multiple variables from MODIS- and Landsat-derived images revealed wide-ranging changes in permafrost landscapes in the Yakutsk region from 2000 to 2011, including changes in snow cover, land surface temperature, vegetation, fires, and lake area, with the latter increasing by 11% to 42% in different parts of the study area (Boike et al. 2016).

At a smaller regional scale, unmanned aerial vehicles (UAVs, drones) equipped with video cameras and other sensors are increasingly used to map permafrost features. These airborne systems (e.g., Fraser et al. 2015) offer the advantages of high spatial resolution (3 cm or less) and an extent of spatial coverage that can be related to satellite imagery (1 to 100 ha), without the interfering effects of cloud cover. At the local scale, automated cameras (e.g., Pienitz et al. 2016) and other in situ instruments (e.g. Boike et al. 2015; Deshpande et al. 2015; Arp et al. 2016) are providing continuous measurements of environmental change, including of ice cover, temperature, turbidity, oxygen, water levels, and other limnological variables in lakes and reservoirs in permafrost landscapes.

Given that disturbances of permafrost systems create safety risks in the North, innovative technologies are needed to provide situational awareness and warning about sudden changes in landscape stability that could lead to collapses in roads, runways, and hillsides.
in and around northern communities. One such technology is distributed temperature systems (DTS) of fiber optic cables that can continuously measure variations in temperature over length scales of thousands of metres; for example, a 3.4 km long DTS system is being used along the Salluit airport access road for the early detection of warming spots that could lead to further damage and where pre-emptive adaptation measures need to be taken (Roger et al. 2015). All of the technologies described above and their ongoing development will continue to enrich the scientific understanding and data sets that underpin landscape modelling to assess the local and global consequences of future change.

An additional step towards developing resilience is the formulation of new design criteria and building codes that take into account the changing northern climate. For example, the development and assessment of new hydroelectric schemes in the far North must now consider not only the changing precipitation regime but also changes in flow paths through eroding permafrost landscapes and the increased sediment loads that may accelerate infilling of reservoirs and affect turbine operations (Cherry et al. 2017). In Canada, an extensive consultation with northern communities, engineers, and permafrost specialists has led to a set of national standards for geotechnical surveys before construction on permafrost (BNQ 2017). Additional standards have been set for drainage systems in northern communities on thawing permafrost landscapes (CSA Group 2015) and for thermosiphons (including monitoring of their performance), building foundations, and snow loading in a changing climate. This “designing for change” is a radical departure from most development projects in the past that have been predicated on long-term stability of the environment. It sometimes involves engineering practices and designs that are more expensive than conventional construction methods, but these are economical in the long run and are now an essential requirement for new or rehabilitated infrastructure in the North (Doré et al. 2016).

These adaptation and monitoring strategies are already proving their worth in the current regime of rapid warming, but they will become increasingly critical for northern safety and sustainable development over the course of this century. In Alaska, the financial costs of climate-related damage to public infrastructure in the absence of adaptation measures have been estimated as 5.5 billion$ for the period 2015 to 2099 under the RCP8.5 scenario, falling to 4.2 billion$ for RCP4.5; the largest source of damage was identified as road flooding followed by damage to buildings caused by permafrost thaw (Melvin et al. 2017). An analysis of the implications of the Paris Accord to limit warming to a global average of 1.5 °C indicated that 4.8 × 10^6 km^2 of permafrost would be lost, rising to 6.6 × 10^6 km^2 (>40% of the current permafrost area) under a 2 °C warmer regime (Chadburn et al. 2017). These estimations underscore the vital need to strive towards a massive reduction in carbon emissions, despite the technological breakthroughs and “Herculean efforts” (Rockström et al. 2017) that will be needed to achieve decarbonization of our global economy.

Conclusions

Permafrost landscapes and human society are integral parts of the larger Earth system and are coupled at multiple scales. At the local scale, human infrastructure affects snow and liquid water – permafrost interactions, which in turn influence the stability of the three-layer permafrost system, its connectivity to adjacent ecosystems, and the provision of geo-ecosystem services from permafrost landscapes to northern communities. Considerable attention now focuses on how these communities can strengthen their resilience in the face of environmental change, and this process requires not only the acquisition of new permafrost knowledge but also its transfer back to northern stakeholders, who can then apply it towards sustainable development and adaptation. This capacity building in the North will be an essential part of coping with local changes in the permafrost system.
At a circumpolar scale, long-term permafrost stability is vulnerable to human-induced climate change, and the geo-ecosystem service role of permafrost in sequestering organic carbon has begun to diminish. The northern Earth system is now moving to a higher energy state, with increased liquid water flow through a much deeper active layer, faster kinetics of all geo-ecosystem processes, and more dynamic interactions, both locally and with the global environment. These changes are also likely to affect the plant and animal ecology of the North, contributing to the global loss of biodiversity. The magnitude and timing of net carbon exchange between the permafrost system and the atmosphere continue to be a source of major uncertainty and concern. In the longer term, only the concerted efforts of all nations towards reduction of greenhouse gas emissions at the scale of the whole Earth system will be effective in slowing the increasingly severe perturbation of the northern landscape and its permafrost geo-ecosystem services.

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